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Special Issue Reprint

Environmental Policy as a Tool for Sustainable Development

Edited by
Konstantinos S. Ioannou, Evangelia Karasmanaki and Georgios Tsantopoulos

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About the Editors

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Editorial

Environmental Policy as a Tool for Sustainable Development

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Over the past 50 years, environmental policy has undergone a profound transformation, evolving from a fragmented, reactive discipline into a cornerstone of global and regional governance. Initially driven by local pollution events and public health concerns, environmental policy now encompasses complex global challenges such as climate change, biodiversity loss, and resource scarcity. The international community, recognizing the transboundary nature of environmental problems, has developed multilateral agreements and institutional frameworks that promote cooperation, accountability, and shared responsibility.

At the global level, milestones such as the Stockholm Conference, the Rio Earth Summit, the Kyoto Protocol, and the Paris Agreement have steadily expanded the scope of environmental governance. These agreements have not only advanced specific goals—such as emission reductions and biodiversity protection—but have also helped institutionalize environmental sustainability as a fundamental principle of international relations and development planning.

The European Union (EU) has played a pioneering role in this evolution, often setting precedents for ambitious environmental legislation and integrated policy frameworks. Tools like the EU Emissions Trading System, the Water Framework Directive, and the European Green Deal, have helped the EU to demonstrate how environmental policy can be strategically aligned with concepts like innovation, economic competitiveness, and social cohesion. The EU's approach on environmental policy reflects a long-term vision of sustainability that incorporates circular economy principles, green finance, digital transformation, and participatory governance.

It is common knowledge that environmental policy today is no longer viewed separately but as deeply interconnected with other policy domains—including health, transport, trade, agriculture, and energy. This shift toward policy integration and systemic thinking marks a critical advancement in how societies respond to environmental challenges. Additionally, emphasis has also shifted from damage control to prevention, resilience-building, and regenerative practices.

As the world faces an ongoing increase in environmental pressures coupled with the urgent need to meet the UN Sustainable Development Goals, the next phase of environmental policy must be characterized by bold action, inclusivity, and adaptability. Future progress will not only depend on the strength of regulatory frameworks but also on the meaningful engagement of stakeholders—governments, businesses, scientists, and citizens alike. Environmental policy must continue to evolve as a dynamic governance instrument, capable of navigating uncertainty while ensuring that ecological integrity and human well-being remain central to sustainable development.

Environmental policy can also be used strategically to achieve sustainable development, while maintaining a balance between economic activity and social welfare. As

our world now faces a multitude of environmental challenges –climate change, resource exhaustion, air and water pollution, deforestation, and biodiversity loss, governments, corporations, and citizens need to work together in order to develop policies that ensure responsible resource management and build resilience. When properly designed, environmental policy is able not only to safeguard natural ecosystems, but also promote innovative solutions, unlock new economic potential, and improve public health. Therefore, it is no longer about whether environmental policy is essential, but how it can be developed to promote sustainability and prosperity for all.

Effective environmental policy is essential for aligning economic progress with ecological responsibility, because organizational decision-making often tends to disregard environmental values. That is mainly because industries' effects on the environment do not become noticeable immediately, while preventing these effects is an economic externality [1,2]. Moreover, there is a tendency to depreciate natural resources by assuming that resources are inexhaustible, even though the risk of resource depletion is greater than ever [3,4]. A solution could be sustainable development, which can be used strategically to balance environmental protection with economic growth [5]. This balance is realizable because sustainable development promotes resource efficiency, waste reduction, and innovation, which, in turn, reduce production costs, create jobs, and attract investments [6].

In the realm of energy transition, environmental policy can play a key role in guiding societies away from fossil fuels and toward renewable energy systems. This can be achieved through the implementation of a variety of ambitious targets and strategic roadmaps, such as the EU Renewable Energy Directive, as well as economic tools like carbon pricing, feed-in tariffs, and clean energy tax credits. Energy efficiency regulations for appliances, buildings, and vehicles also contribute significantly. Additionally, public support for research and innovation—often stimulated through environmental policy—has advanced technologies in solar, wind, battery storage, and grid integration. By internalizing the external costs of fossil fuels, environmental policy reshapes market dynamics and creates enabling conditions for a decarbonized energy system.

Climate change mitigation is another domain where environmental policy has demonstrated significant impact. Countries are now bound by international agreements, such as the Paris Agreement, to establish legally binding emission reduction targets. These targets are supported by domestic policies regulating emissions from power generation to transportation and heavy industry. In addition to direct regulation, environmental policies encourage the adoption of nature-based solutions like afforestation and wetland restoration and support sustainable urbanization through public transport infrastructure and green building codes. Instruments such as the EU Emissions Trading System serve as market-based mechanisms that incentivize carbon reduction by putting a price on emissions.

Biodiversity conservation also relies heavily on environmental policy to establish legal protections and incentivize ecosystem stewardship. Governments deploy protected area designations, habitat conservation plans, and environmental impact assessments to combat ecological degradation. Policy mechanisms such as payments for ecosystem services, enforcement of anti-poaching laws, and restrictions on land-use change all contribute to conserving species and habitats. Yet conservation efforts are increasingly shifting toward system-wide resilience, focusing not only on preservation but also on ecological restoration and sustainable land-use planning.

In agriculture, environmental policy helps steer the sector toward sustainability by embedding environmental considerations into subsidy schemes and regulatory frameworks. Agri-environmental programs reward farmers for adopting practices that conserve biodiversity, reduce greenhouse gas emissions, and maintain soil health. These policies

may include restrictions on harmful inputs like pesticides, support for organic agriculture, and guidelines for land-use that prevent deforestation and erosion. The European Union's Common Agricultural Policy (CAP) for 2023–2027 exemplifies this integration by tying financial support to environmental performance, encouraging climate-smart and biodiversity-friendly farming techniques.

Across all these sectors, environmental policy serves not only as a control mechanism but as a framework for innovation, equity, and resilience. Good governance is essential for effective implementation, requiring coordination across levels of government and sectors. Social justice must also be a core consideration, as policies need to ensure that marginalized and vulnerable populations are not disproportionately affected. Moreover, data systems and monitoring tools are vital for tracking progress, evaluating policy outcomes, and enabling adaptive management.

Furthermore, environmental policy can be a tool for sustainable development because it seeks to create a favorable context where economic development will not only adhere to environmental protection measures, but also to the principles of sustainable development. Due to the constant efforts of policymakers, scientists, international organizations, governments, and environmental groups, there is now a wide array of regulatory, market, and voluntary instruments in place [7]. This should not mean, however, that there is no longer the need for environmental policy, as it is now more important than ever to ensure a robust environmental framework that acts with quick reflexes to the ongoing environmental problems and the new challenges to sustainable development [8]. At the same time, environmental policy is challenged more than ever as new global pressures and threats drive governments to rethink environmental policies and seek ways to reconcile environmental and economic objectives. More than ever, environmental policy making is now full of uncertainty, conflicting objectives, and numerous sources of decision and control authorities. In this context, policymakers need a constant flow of information that will allow them to establish priorities, design new strategies, and make policy decisions.

To facilitate the task of environmental policy making, the aim of this Special Issue was to collate original research papers, reviews, and essays that address the application of environmental policies as tools for sustainable development. We invited authors whose research utilizes both traditional and innovative approaches including surveys, databases, and modeling applications, as well as authors with an expertise in the design of policy measures, policy frameworks, evaluation of current environmental policies, and the underlying connections between policy measures, climate change mitigation, and sustainability.

The Special Issue includes the following works:

1. Marek Zieliński, Wojciech Józwiak, Agata Zak and Tomasz Rokicki: "Development of Eco-Schemes as an Important Environmental Measure in Areas Facing Natural or Other Specific Constraints Under the Common Agriculture Policy 2023–2027: Evidence from Poland".
2. Teodor Kalpakchiev, Brent Jacobs, Markus Fraundorfer, Julia Martin-Ortega and Dana Cordell: "Creating an Alternative Governance for Phosphorus Circularity Through Framings That Strengthen Intersectoral Policy Coherence in the EU: Constraints and Implementation Possibilities".
3. Andrey Afanasiev, Olga Kandinskaia, Snezana Eminidou, Andreas Sousanis: "Hydrogen Valley in Cyprus: Insights and Strategies for Citizen Engagement".
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6. Xiao Liu, Yue Zhu. "Research on the Impact Mechanism of ETS on Green Innovation in China's High-Carbon Industries: A Perspective of Enterprise Heterogeneity".
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21. Arnold J. Bomans, Peter Roessingh: "Decision Change: The First Step to System Change".

Finally, we would like to express our most sincere gratitude to the people that helped us complete this Special Issue successfully; it would be an understatement to say that without their help this Special Issue would have been impossible. First and foremost, we are deeply grateful to all authors who responded to our invitation and trusted us with their works. We would also like to express our deepest appreciation to Ailsa Sun, our Special Issue's Managing Editor, for her constant support, attentiveness, and guidance. We would also like to acknowledge the efforts and support of the journal's Editorial Board members as well as the academic editors and reviewers responsible for every submission. The success of the Special Issue was to a great extent due to their meticulousness and competence. Having served as Guest Editors for this journal, we can, with certainty, state that the Sustainability journal will continue publishing high-quality research that provides state-of-the-art knowledge in the field of environmental policy and sustainable development. We would also like to express the

hope that this Special Issue will lead to new research directions that will, in turn, improve the design and implementation of environmental policy.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ludwig, D.; Mangel, M.; Haddad, B. Ecology, conservation and public policy. *Annu. Rev. Ecol. Syst.* **2001**, *32*, 481–517. [CrossRef]
2. Kraft, M.E. *Environmental Policy and Politics*; Routledge: New York, NY, USA, 2021; ISBN 9781003106265.
3. Giddings, B.; Hopwood, B.; O'Brien, G. Environment, economy and society: Fitting them together into sustainable development. *Sustain. Dev.* **2002**, *10*, 187–196. [CrossRef]
4. Armstrong, J.H. Modeling effective local government climate policies that exceed state targets. *Energy Policy* **2019**, *132*, 15–26. [CrossRef]
5. Ruggerio, C.A. Sustainability and sustainable development: A review of principles and definitions. *Sci. Total Environ.* **2021**, *786*, 147481. [CrossRef] [PubMed]
6. Fu, C.; Lu, L.; Pirabi, M. Advancing green finance: A review of sustainable development. *Digit. Econ. Sustain. Dev.* **2023**, *1*, 20. [CrossRef]
7. Michaels, S. Matching knowledge brokering strategies to environmental policy problems and settings. *Environ. Sci. Policy* **2009**, *12*, 994–1011. [CrossRef]
8. Waheed, A.; Shahid Khan, M.; Warraich, M.A.; Ali, M.A. Environmental policy vs. Environmental innovation: An examination of policies disclosure on sustainable development from stakeholder theory perspective. *Sustain. Dev.* **2024**, *32*, 2506–2516. [CrossRef]

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Article

Development of Eco-Schemes as an Important Environmental Measure in Areas Facing Natural or Other Specific Constraints Under the Common Agriculture Policy 2023–2027: Evidence from Poland

Marek Zieliński [1,*], Wojciech Józwiak [1,*], Agata Żak [1] and Tomasz Rokicki [2]

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Abstract: Institutional environmental measures play a fundamental role in the Common Agricultural Policy (CAP) 2023–2027, which primarily focuses on eco-schemes and for which the EU Member States must allocate part of their direct payment budget. The total budget under eco-schemes in the EU is an important part of Pillar I of the CAP 2023–2027. The aim of this study is to determine the capacity of Polish agriculture in ANCs to adopt practices under eco-schemes in the first year (2023) of the CAP 2023–2027. In the international literature, there is an apparent paucity of such analyses conducted for the newly designated ANCs in the EU Member States based on the European Commission's guidelines under the CAP 2014–2020 and applicable under the CAP 2023–2027. Practices under eco-schemes are now fundamental for EU agriculture, increasing soil fertility, using rational fertilization and, as a result, improving the quality of products offered to consumers. It was pointed out that at this moment in ANCs, the use of eco-schemes is not satisfactory. The conclusions emphasized that in the EU, including Poland, eco-schemes should be implemented by as many farmers as possible, regardless of the size of the farm they have and the natural conditions in which they carry out agricultural production.

Keywords: agriculture; eco-schemes; ANCs areas; natural handicaps; EU Common Agricultural Policy (CAP)

1. Introduction

In recent years in the European Union (EU), there have been increasing societal expectations and requirements related to the necessity of reliably assessing the actions taken by farms toward the protection of the natural environment, particularly in relation to the European Common Agricultural Policy (EU CAP) [1]. Farmers, for their own and society's benefit, should take care of the condition of the agricultural land they use. This is all the more so because, globally, about 1/3 of the total area of agricultural land is currently undergoing at least moderate degradation caused, among other things, by erosion leading to a decline in soil organic matter [2]. For example, in the EU, about 60–70% of soils are in an unsatisfactory condition, caused by their unsustainable use [3]. These soils are increasingly degraded due to erosion, compaction, pollution, salinization, desertification, and a loss of organic matter and biodiversity [4–6]. This state of affairs is particularly unfavorable when agriculture is treated as an important source of many public goods that

are of increasing value to societies. After all, healthy soils provide biomass, raw materials and food, while regulating the climate and the water and nutrient cycles [2,7].

In agriculture in the EU, including that of Poland, one of the important challenges for farms is meeting the current requirements for natural environment protection under conditions of local land abandonment in areas with difficult farming conditions established within areas facing natural or other specific constraints (ANCs) [8–10]. This is particularly significant given that ANCs in Poland account for 58.7% of the total agricultural area. In this context, it should also be added that in the EU as a whole, the share of these areas is similar, at 58.6% of the total agricultural area [11]. This means that in the EU, including Poland, ANCs play an important role in contributing to the total production potential of agriculture. A lack of concern for soil fertility in ANCs in the EU reduces land productivity and yields, and negatively affects the level of agricultural production, food security, international agri-food markets and the global economy. As a result, this state of affairs has not only high environmental costs but also additional negative social impacts.

An important asset of ANCs—particularly valued by EU societies today—is their often high natural value, which predisposes them to providing a range of environmental goods, including high biodiversity and diversified landscapes [12,13]. However, the weaknesses of ANCs include the presence of low-quality soils and, in the case of mountain ANCs, difficult terrain and a much shorter growing season for crops than in lowland areas, which significantly limits the selection of beneficial crops. Farms in these areas, therefore, often incur higher production costs and obtain lower production results [14,15]. ANCs, therefore, face serious challenges in sustaining agriculture as a source of both high-quality market goods and environmental goods, especially since they have been experiencing a steady decline in agricultural land use or conversion to other uses for many years.

The EU sees great potential for environmental protection through agriculture in ANCs and links the benefits of supporting them to sustaining economic viability and raising environmental awareness and willingness among farmers in these areas to make changes related to better environmental protection. An important opportunity to support agriculture in these areas could be participating in institutional environmental measures under CAP 2023–2027.

Institutional environmental measures play a fundamental role in the CAP 2023–2027. First of all, these are the eco-schemes to which the EU Member States must allocate a part of their direct payment budget under the current agricultural policy [16,17]. The total budget under eco-schemes is EUR 44.7 billion against the background of EUR 190 billion under the entire Pillar I of the CAP 2023–2027 [18]. According to the European Commission, the EU Member States should dedicate at least 25% of their Pillar I CAP 2023–2027 budget to eco-scheme payments. However, it is possible to reduce their share in the total amount of direct payments if more support funds are allocated to environmental measures in the Pillar II CAP 2023–2027 [19]. France has the largest amount dedicated to the eco-schemes (EUR 8.53 billion), while The Netherlands has the largest share (32%) in the total budget under the Pillar I of the CAP 2023–2027 [18]. The eco-schemes are mandatory for the EU Member States, but their implementation by farmers is voluntary [20,21]. According to the European Commission, the eco-schemes should be prioritized for environmental protection and should be designed to meet the specific needs and priorities of a given EU Member State. Every EU Member State has the flexibility to customize their eco-schemes to specific national environmental and climate needs [22,23].

The quality of natural conditions for farming generally affects the direction, organization and scale of agricultural production, as well as the production and economic effects obtained. In this situation, questions arise about the propensity of farms from areas with different natural conditions to implement eco-schemes.

In this study, we proposed the hypothesis that the areas that should be particularly predestined for the development of eco-schemes are those with less favorable natural conditions for agriculture, where there is generally a need for additional measures regarding soil conservation. Such practices are necessary here and result from the often low natural organic matter content of arable land, the threat of increased erosion and the consequent loss of organic carbon, as well as the need to maintain permanent grasslands, which are often characterized in these areas by a high natural value. On the other hand, eco-schemes have a lot to offer agriculture, regardless of the natural conditions, as they increase soil fertility, use rational fertilization and, as a result, improve the quality of the products offered. In addition, the payments used for them can account for a significant part of the farm income of eco-schemes' beneficiaries and influence their decisions regarding production development.

This raises questions concerning the type, number, and scale of the eco-scheme practices implemented by Polish farms in ANCs under the CAP 2023–2027. This study is intended to fill the research gap regarding the determination of the capacity of Polish agriculture in ANCs to absorb eco-scheme practices under the CAP 2023–2027. There is an apparent paucity in the international literature of such analyses conducted for the newly designated ANCs that are based on the European Commission's guidelines under the CAP 2014–2020 and applicable under the CAP 2023–2027.

2. Research Background

2.1. The Importance of ANCs in the EU: Theoretical Approach

Modern economic theory, in order to interpret the changes in economic reality well, including those related to agriculture, should take into account the choices made by individuals, not only from the aspect of personal economic wellness, but also from environmental and social aspects. In the context of preserving agricultural areas in good condition, this constatation becomes fundamentally importance. In order to keep agricultural soils in good condition, the presence of institutional rules of conduct that are capable of regulating and motivating expected behavior is essential. In European Union (EU) agriculture, this is served by the Common Agricultural Policy (CAP), which is revised every few years and is becoming increasingly sensitive to public concerns about the environmental. Institutional measures aimed at protecting the natural environment play a major role in the CAP 2023–2027 and, as a result, it supports the goals of the European Green Deal Strategy for 2050. On the other hand, however, the current EU agricultural policy is expected to support agriculture in achieving a balance between providing society with a good natural environment and ensuring a satisfactory agricultural income for farmers.

For the European Commission, one of its primary objectives under the European Green Deal strategy, its thematic strategies, and the CAP 2023–2027 is to strengthen existing efforts to protect the natural environment, including in ANCs, which are often an important source of environmental goods valued by society, such as diverse landscapes and high biodiversity [1,3,24–29]. Hence, in ANCs, it becomes particularly important to raise awareness and willingness among farmers to protect the natural environment, as well as support the economic viability of often marginally located rural areas of high social importance [30–34]. This is all the more so because farms in these areas generally have poorer economic performance and fewer opportunities for development compared to farms located outside ANCs [14,35,36]. The European Union supports these areas under European policy from 1975. Currently, this support is used to continue agricultural production in disadvantaged areas and to maintain and promote sustainable farming systems there. In other words, support for farming in ANCs is treated as compensation for producing not only market goods, but goods and services of the environment, which are important for society but not rewarded by the market. The benefits of this support involve both raising farmers'

awareness and inclination to protect the natural environment, and sustaining the vitality of often marginally located rural areas of great importance to society. On the other hand, given the high importance of ANCs in the EU, they play an important role in contributing to food self-sufficiency for the European community, including Poland, and preserving the EU's ability to export agri-food products. The need to maintain agricultural production in ANCs also arises from the need to protect soils from degradation (erosion, acidification, soil organic matter losses), maintain many of their environmental functions, including retention, and maintain a diverse and valuable landscape. Thus, in the EU, including Poland, ANCs, in addition to market functions, also have a number of functions related to the protection of the natural environment, for which they are particularly predestined. This is evidenced by the large presence of areas with extensive agriculture in them, meeting the requirements of the European Union under the concept of High Nature Value farmlands (HNVf) and Natura 2000 areas. In addition, farmers in these areas are strongly inclined to take measures that specifically enhance environmental goods under the EU CAP [37].

In the EU Member States, the natural farming conditions are characterized by spatial variability and often a high proportion of ANCs. As mentioned in the introduction, in the European Union, ANCs currently represent 58.6% of the total agricultural area [11]. Of these, ANCs with natural constraints dominate (33.5%), followed by mountain areas (17.0%) and areas with specific constraints (8.1%). Malta and Luxembourg have the highest share of ANCs, with ANCs comprising 100% of each of their total agricultural areas. Latvia (88.8%) and Luxembourg (85.8%) have the highest share of ANCs with natural constraints; France (22.5%) and Luxembourg (14.2%) have the highest share of ANCs with specific constraints; and Slovenia (55.8%) and Finland (52.7%) have the highest share of mountain ANCs. Denmark (2.5%), The Netherlands (11.9%), and Hungary (16.5%) have the smallest total share of ANCs [5] (Figure 1 and Table 1).

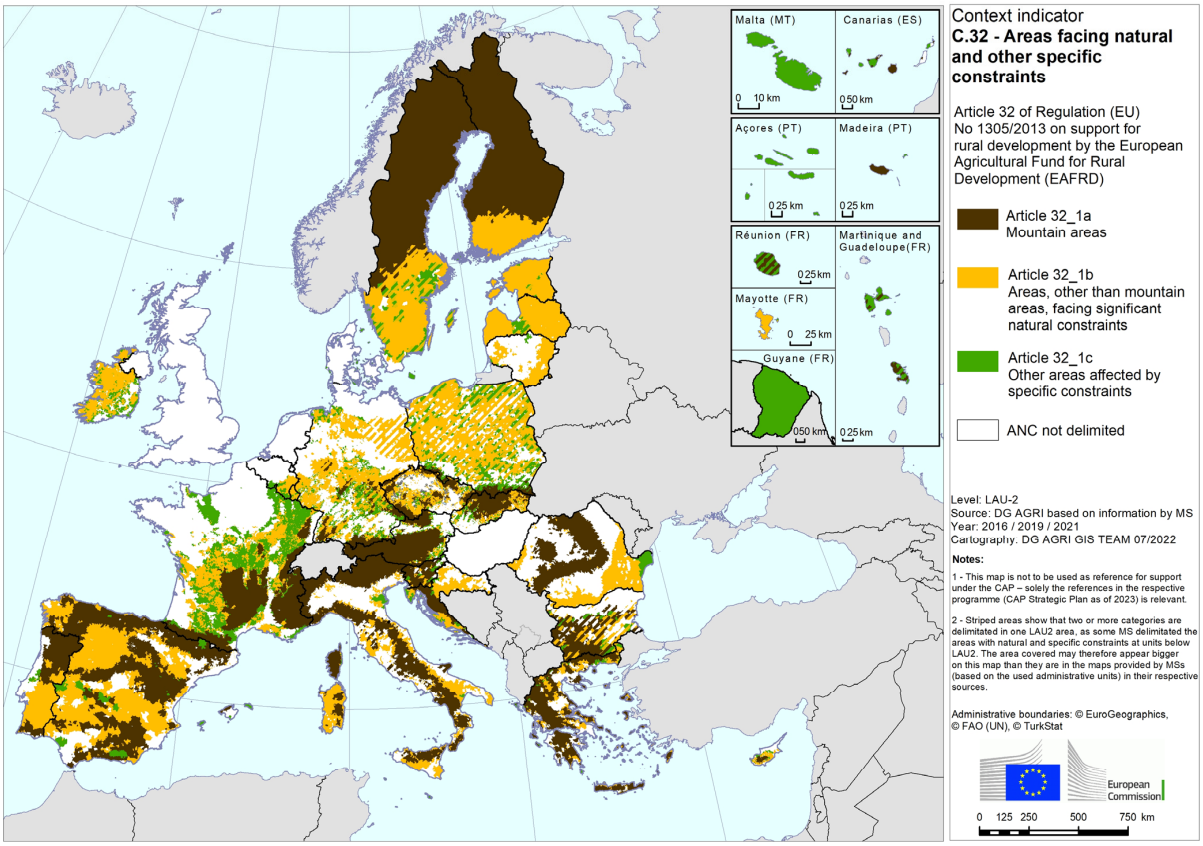


Figure 1. Distribution of ANCs in the EU. Source: European Commission, https://agridata.ec.europa.eu/extensions/IndicatorsEnvironmental/LessFavouredAreas.html (accessed on 17 January 2025).

Table 1. Percentage share of ANCs in total utilized agricultural area (UAA) in EU-27 in 2021 (%).

	ANCs with Natural Constraints	ANCs with Specific Constraints	Mountain ANCs	Total Share of ANCs
EU-27	33.5%	8.1%	17.0%	58.6%
Malta	0.0%	100.0%	0.0%	100.0%
Luxembourg	85.8%	14.2%	0.0%	100.0%
Finland	46.0%	0.9%	52.7%	99.6%
Latvia	88.8%	4.1%	0.0%	92.9%
Portugal	60.7%	3.8%	25.5%	90.0%
Spain	52.9%	3.0%	30.6%	86.5%
Ireland	68.5%	8.4%	0.0%	76.9%
Slovenia	8.3%	12.1%	55.8%	76.2%
Cyprus	63.8%	3.8%	6.5%	74.1%
Greece	22.4%	4.1%	44.2%	70.7%
Austria	5.7%	8.0%	49.6%	63.3%
Slovakia	29.0%	8.4%	25.4%	62.8%
Italy	26.5%	1.8%	31.6%	59.9%
Poland	47.0%	10.0%	1.7%	58.7%
EU-27	33.5%	8.1%	17.0%	58.6%
Czech Republic	35.3%	6.5%	14.7%	56.5%
France	15.0%	22.5%	16.4%	53.9%
Romania	33.6%	1.4%	15.1%	50.1%
Sweden	37.2%	1.3%	10.7%	49.2%
Germany	32.2%	7.0%	3.5%	42.7%
Croatia	34.7%	3.5%	3.1%	41.3%
Estonia	35.6%	5.3%	0.0%	40.9%
Lithuania	30.5%	2.7%	0.0%	33.2%
Bulgaria	5.5%	0.5%	19.2%	25.2%
Belgium	13.6%	9.8%	0.0%	23.4%
The Netherlands	0.0%	11.9%	0.0%	11.9%
Hungary	0.0%	9.1%	0.0%	9.1%
Denmark	0.0%	2.5%	0.0%	2.5%

Source: [11].

In the EU, 23 Member States have allocated additional support to ANCs under Pillar II of the CAP 2023–2027 (Figure 2). The budget supporting ANCs is set at EUR 18,716.2 million, representing 17% of the total Pillar II budget of the CAP 2023–2027. The largest budgets for this measure are allocated to France (EUR 5500 million), Poland (EUR 1480 million), Italy (EUR 1460.2 million), Greece (EUR 1275.4 million), and Ireland (EUR 1250 million). Denmark (EUR 13.1 million), Malta (EUR 14 million), and Cyprus (EUR 26.5 million) have the smallest budgets for the ANC measure [38].

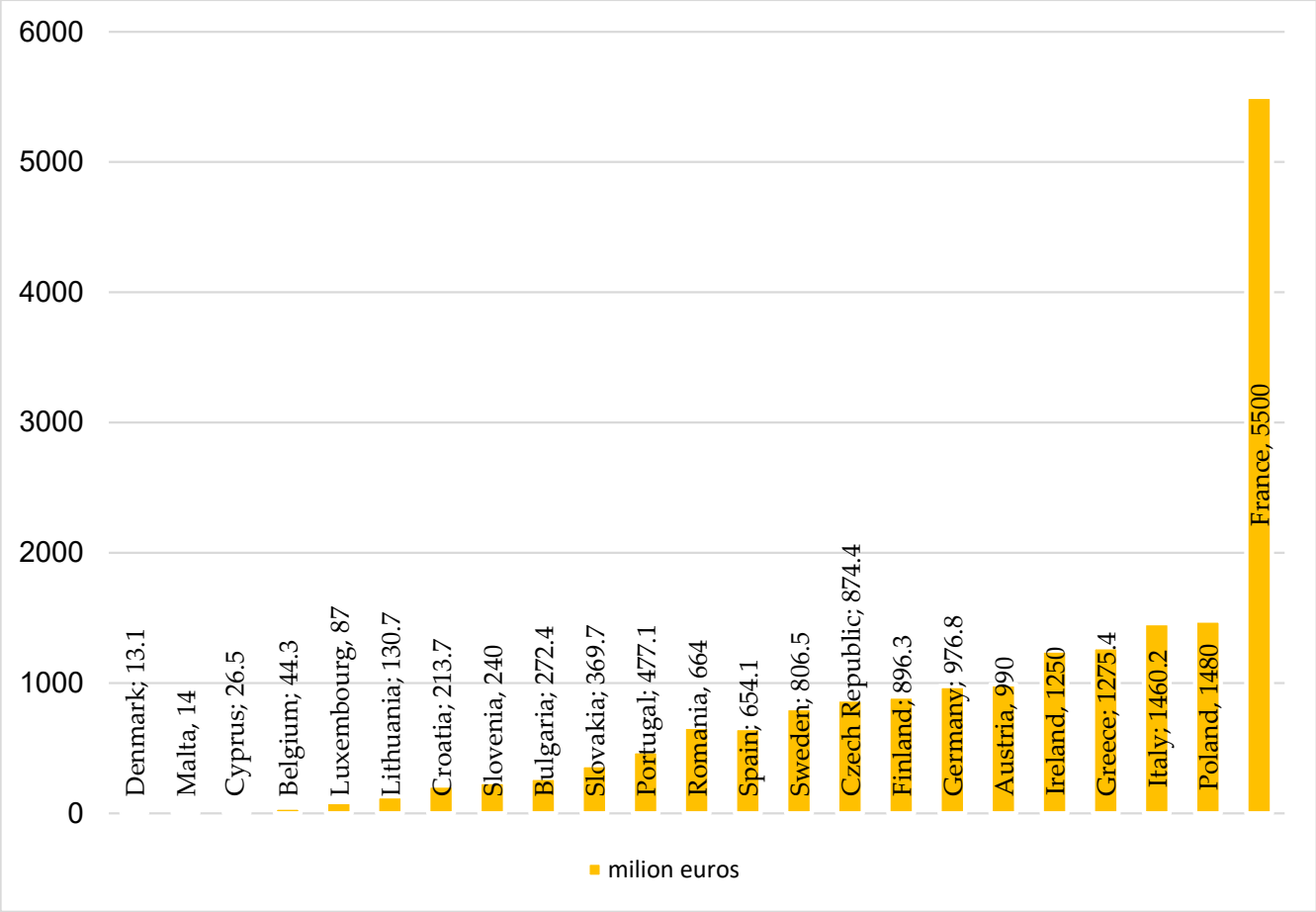


Figure 2. Amount of support for ANCs (in EUR million) in the EU Member States under the CAP 2023–2027. Source: [38].

2.2. Eco-Schemes as an Important Environmental Measure Under the CAP 2023–2027

Eco-schemes are a new component of the direct payment system under the CAP 2023–2027, supporting the implementation of practices that are beneficial to the environment, climate and animal welfare [20,23]. These are annual, paid practices that are adjusted to the conditions and needs of the EU Member States to meet the environmental and climate objectives of current European policy for the protection of soil, water, climate, animal welfare and biodiversity in agricultural production [39,40]. In the EU Member States, the eco-schemes are designed to promote practices that contribute to improving agricultural income by increasing soil fertility, rational fertilization, and crop quality. These subsidies are able to account for a significant part of farmers' income and influence their decision-making regarding production development [41]. The eco-schemes, together with other environmental measures under the current European policy, will play an important role in the EU's efforts to achieve the goals of the European Green Deal. There is no doubt that the EU needs multifaceted eco-schemes with solid funding, clear goals and proven benefits to improve agricultural sustainability [42]. However, they must be continuously evaluated in farms in order to achieve correct implementation and deliver the best economic and environmental results [43]. Technological innovations, including satellite solutions applied to EU agriculture, will have much to offer in this area [44]. In CAP 2023–2027, the total budget under the eco-schemes is EUR 44.7 billion. France (EUR 8.53 billion), Spain (EUR 5.55 billion), Germany (EUR 4.94 billion), Italy (EUR 4.4 billion) and Poland (EUR 4.33 billion) have the largest eco-scheme budget. In contrast, this budget is smallest in Cyprus, Luxembourg and Malta, where agricultural production is carried out on a small area relative to other EU Member States (Figure 3). EU countries have different

levels of support for eco-schemes, as a result of having different areas of UAA to which direct payments are due. Eco-schemes are part of direct payments that are dedicated specifically to the protection of the natural environment. At present, eco-schemes have taken hold to varying degrees in EU countries. Given their importance in the protection of the natural environment and the increasingly negative changes in agricultural markets, their use is likely to grow in EU agriculture.

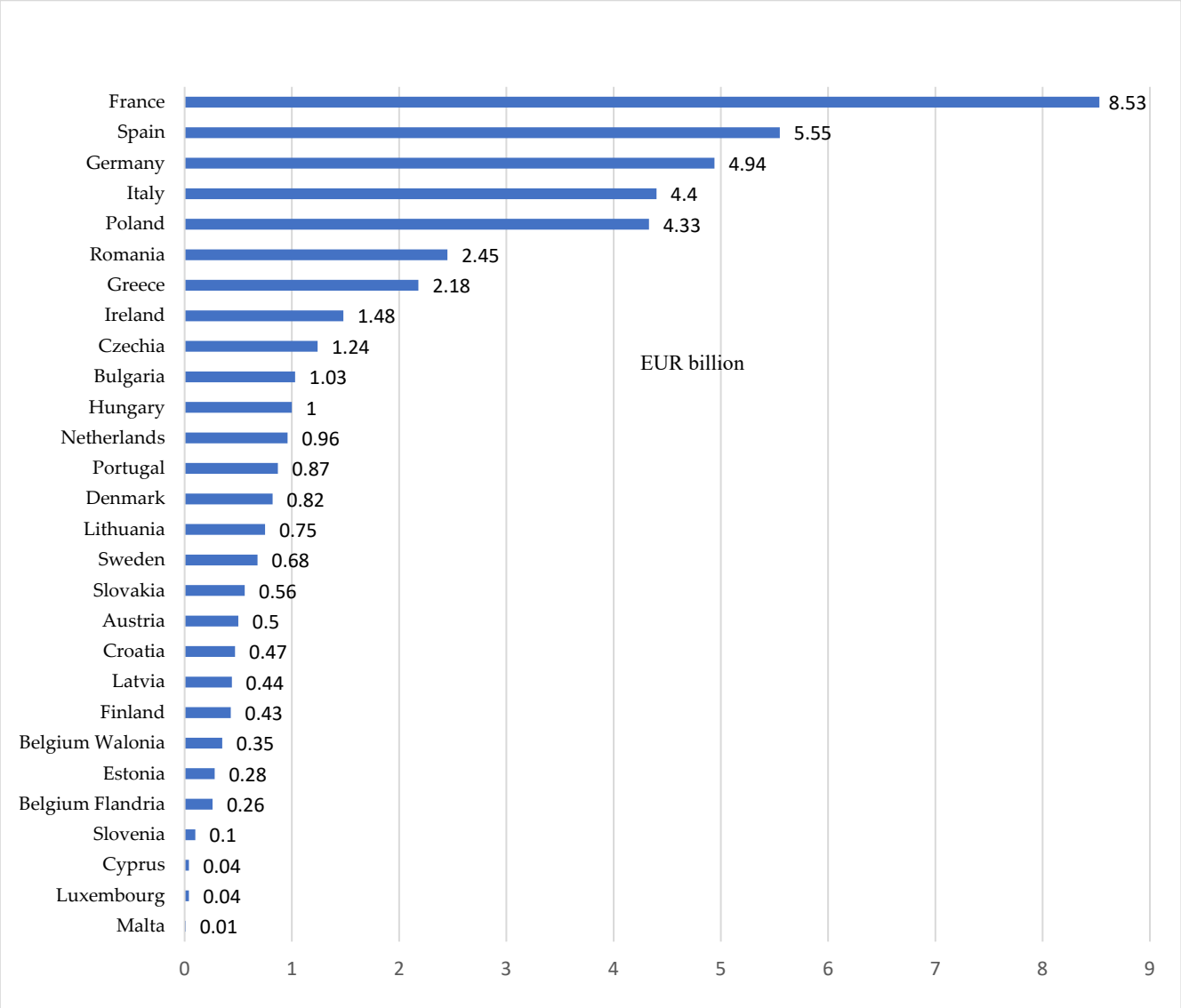


Figure 3. Funds under eco-schemes payments (in EUR billion) in the EU Member States under the CAP 2023–2027. Source: [18].

According to the European Commission's findings, the EU Member States should allocate at least 25% of their budget for Pillar I of the CAP 2023–2027 to eco-scheme payments. However, it is possible to reduce their share of the total amount of direct payments if a proportionally larger amount of support funds is allocated to environmental measures in Pillar II of the CAP 2023–2027 [19]. It turns out that 13 of the EU Member States have contributed 25% of their budget for Pillar I of the CAP 2023–2027 to the eco-schemes. In six EU Member States, their budget is at a level higher than 25% for Pillar I of the CAP 2023–2027. The Netherlands (32%) and Czechia (30%) contribute the largest share of their budget for Pillar I of the CAP 2023–2027 to eco-schemes. The smallest share of the eco-schemes is held by Hungary, Austria and Slovenia, with 15% each (Figure 4).

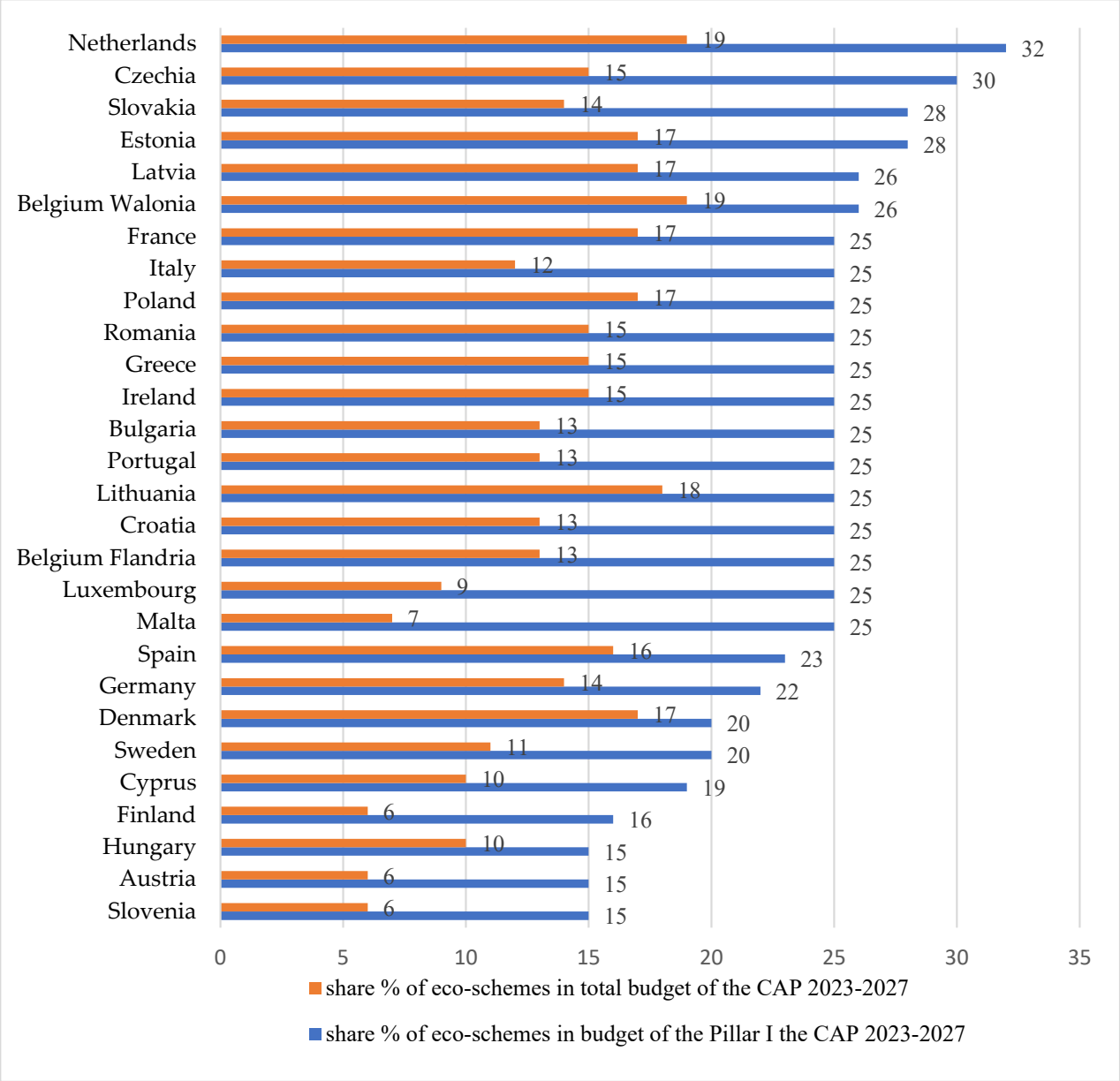


Figure 4. Share (%) of the eco-scheme payments in the Pillar I budget and total budget (Pillar I and Pillar II) under the CAP 2023-2027. Source: [18].

In the EU Member States, 158 eco-schemes have been prepared (Figure 5). They most often concern the protection of soils (47 practices), landscape and biodiversity (30). In contrast, they are most rarely used to protect water and wetlands. It should be noted that in some EU Member States, organic farming has also been included within the eco-schemes. In addition, in the EU member states, six eco-schemes are not related to a specific land use on farms and concern the entire farm, i.e., they oblige the farm to allocate all agricultural land to the eco-schemes [18].

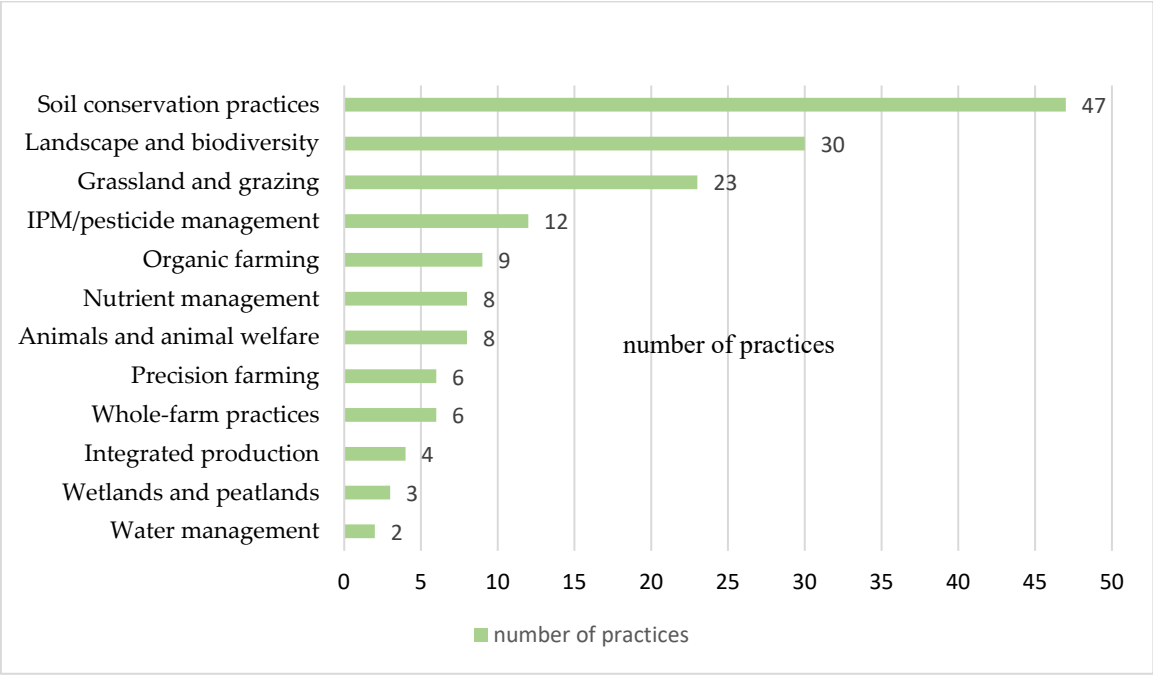


Figure 5. Number of practices under the eco-schemes dedicated to specific areas related to environmental protection and animal welfare in the EU Member States under the CAP 2023–2027. Source: [18].

3. Materials and Methods

3.1. Materials

This study analyzed thirteen practices within five area-based eco-schemes that were available to Polish farms under the EU CAP 2023–2027 in 2023 (Table 2). Relevant data on the number of beneficiaries, as well as the scale and territorial distribution of applied practices within the eco-schemes, were taken from the database of the Agency for Restructuring and Modernization of Agriculture (ARMA); in Poland, this serves as the public institution implementing direct payments under the current CAP.

Table 2. The eco-schemes and their practices implemented in Polish agriculture under the CAP 2023–2027 in 2023.

Eco-Scheme/Practice Within an Eco-Scheme	
1. Carbon farming and nutrient management	1.1. Extensive permanent grassland with livestock 1.2. Winter catch crops/intercrops 1.3. Fertilization plans (basic variant) 1.4. Fertilization plans (liming variant) 1.5. Diversified sowing structure 1.6. Mixing solid manure on arable land within 12 h of application 1.7. Using liquid manure with methods other than splashing 1.8. Reduced tillage systems 1.9. Mixing straw with soil
2. Areas with melliferous plants	
3. Water retention on permanent grassland	
4. Integrated plant production	
5. Biological plant protection	

Source: MARD 2023.

3.2. Methodsc

The distribution of beneficiary farms, the area of agricultural land, and the number and type of eco-schemes implemented were established by considering the natural conditions. For Polish holdings, this was achieved by conducting relevant analyses of the agriculture within communes where at least 75% of the total utilized agricultural areas (UAAs) were in ANCs, compared to the total agriculture (Figures 6 and 7). In Poland, the current delimitation of ANCs was carried out by the Institute of Soil Science and Plant Cultivation—State Research Institute (IUNG PIB) and the Institute of Agricultural and Food Economics—National Research Institute (IERiGŻ PIB) (including by the authors of this study) in 2019, on behalf of the Ministry of Agriculture and Rural Development (MARD) and the European Commission [13]. The main advantage of using the newly designated ANCs in the EU is the use of the same delimitation criteria in the member states. The results of this analysis can therefore be used in other EU countries and beyond for comparative analysis.

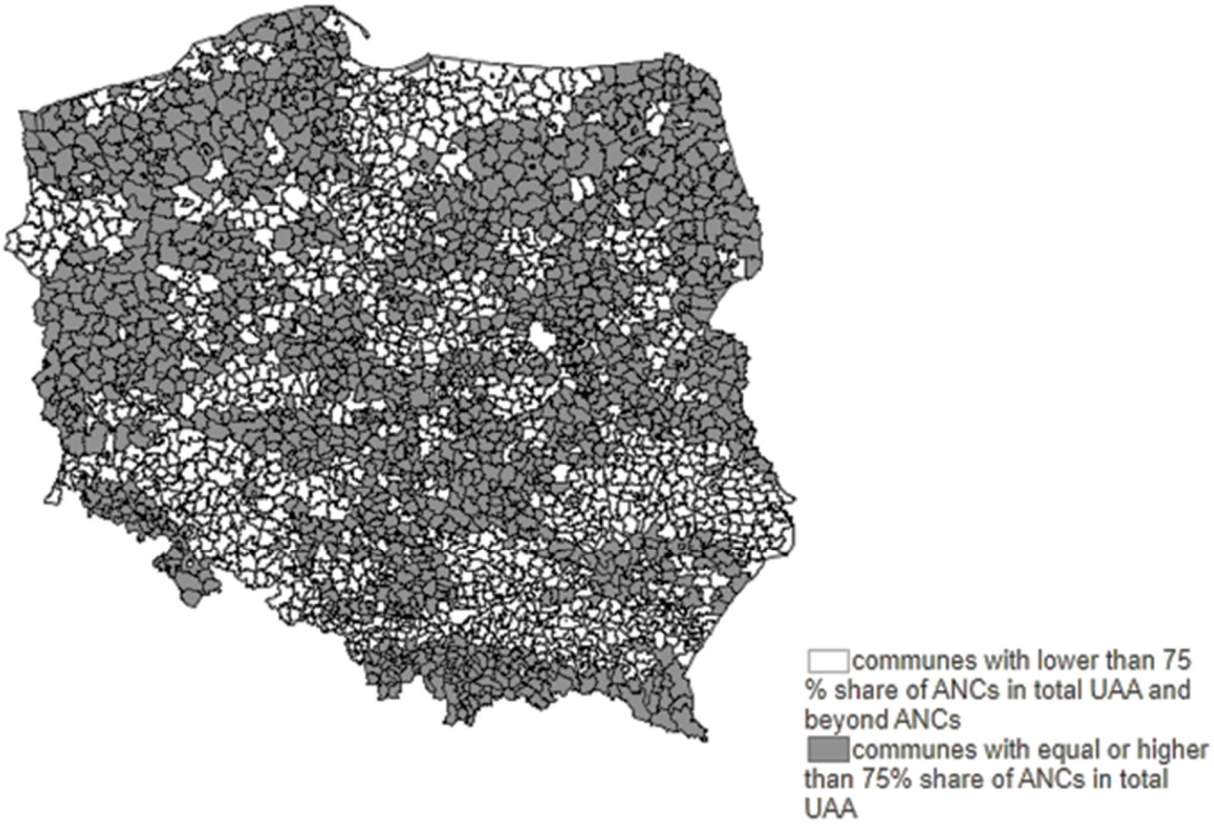


Figure 6. Distribution of ANCs by communes in Poland. Source: Own study.

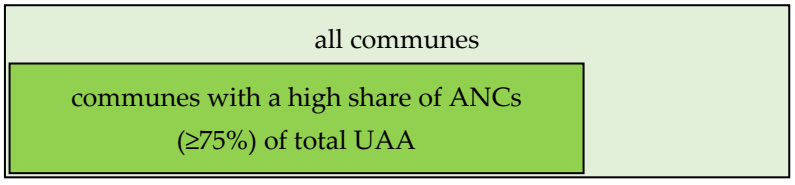


Figure 7. Schematic diagram of the analysis of the agriculture within separate groups of communes based on the presence and severity of ANCs in Poland. Source: Own study.

4. Results

4.1. State of ANCs in Poland

In Poland, agriculture operating in difficult and even particularly difficult soil conditions is of great importance, and there is a need for additional efforts to protect them effectively.

These efforts are due to the low natural organic matter content of soils, where the effects of erosion and the consequent loss of organic carbon are quickly visible. In Polish agriculture, these areas play an important role. These facts indicate the existing threats posed by the further degradation of the country's soils and the need to take preventive measures. In Poland, ANCs areas currently account for 58.7% of the UAA, including 47% with natural constraints, 10% with specific constraints, and 1.7% with mountainous areas. In the EU, their share is slightly lower, at 58.6% [11,45].

Since 2019, ANCs in Poland have been divided into five zones: (1) natural constraints Zone I; (2) natural constraints Zone II; (3) specific type Zone I; (4) specific type Zone II; and (5) mountain type (Figure 8). These areas are found in 2149 communes, representing 86.8% of all communes. In 1299 communes, their share is equal to or greater than 75% of the total UAA; these are referred to as communes with a high share of ANCs (Figure 8) [45].

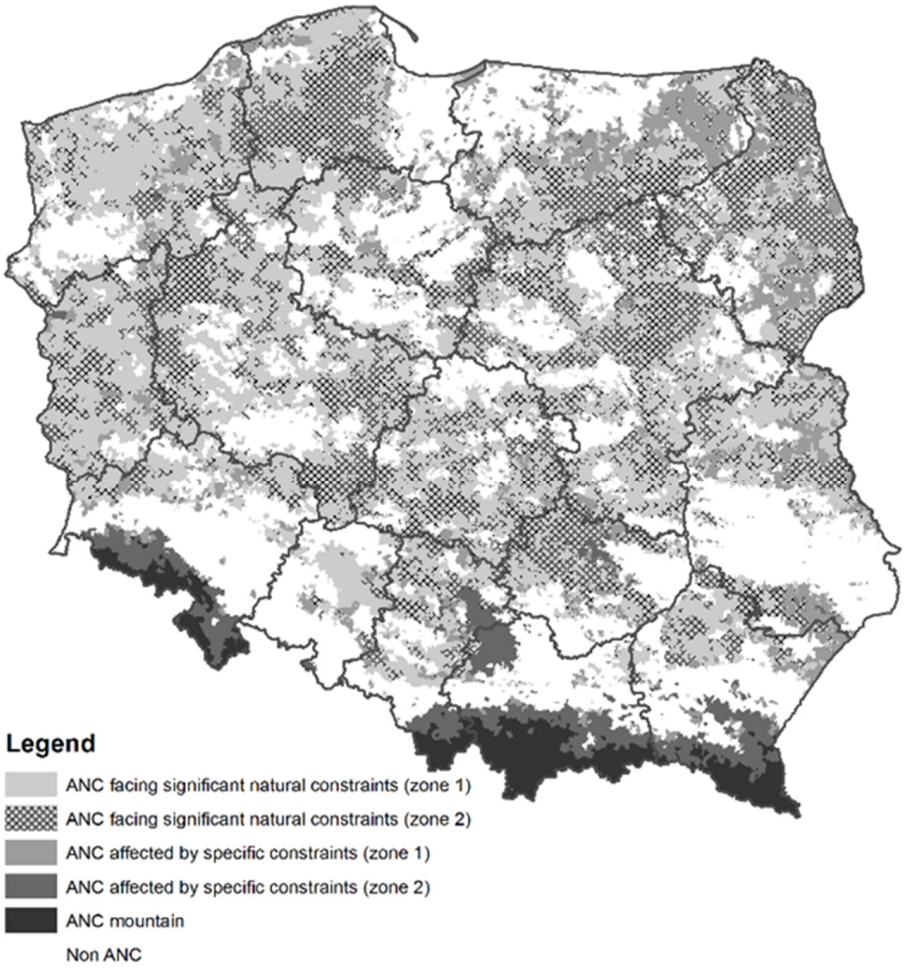


Figure 8. Ranges of areas meeting the criteria of current ANCs in Poland. Source: [45].

4.2. State of Agriculture in Poland, Including ANCs Areas and the Role of Eco-Schemes

Polish agriculture is characterized primarily by a diversity of natural regional conditions. It is also characterized by variations in the strength and economic condition of farms depending on their size, expressed in hectares of agricultural land, their economic size and the type and organization (specialization) of production [46].

In Poland in 2023, there were 1235.2 thousand agricultural farms participating in the CAP 2023–2027. Communes with at least 75% ANCs contained 49.7% of the total number of farms, with these engaging in agricultural production on 47.3% of the total Utilized Agricultural Area (UAA) (Table 3).

Table 3. Selected organizational characteristics of agriculture in Poland, including in communes with a high share of ANCs in 2023.

Specification	All Communes	Included Communes with a High Share of ANCs
The number of agricultural holdings, including participating holdings (thousand):	1234.3	613.2
- in eco-schemes (thous.)	428.3	187.7
UAA area (thousand ha), including UAA area of participating holdings:	14,096.1	6670.1
- in eco-schemes (thousand ha)	8897.9	3495.0

Source: Own study based on ARMA data.

In 2023, 428.3 thousand farms applied for area-based eco-schemes, representing 1/3 of all farms in the country. These farms managed a total of 8897.9 thousand hectares of agricultural land. It should be emphasized, in these farms, the implementation of eco-schemes took place on all or part of their agricultural land, in addition, a different number of practices were implemented on this area. The most frequently chosen practice was the mixing of straw into soil, while the practice covering the largest area was reduced tillage systems [47]. Based on the data in Figure 9, which shows the share of farms covered by eco-schemes in the commune, it should be emphasized that in 2023, farms from regions with a higher level of agricultural development were more likely to participate in these measures.

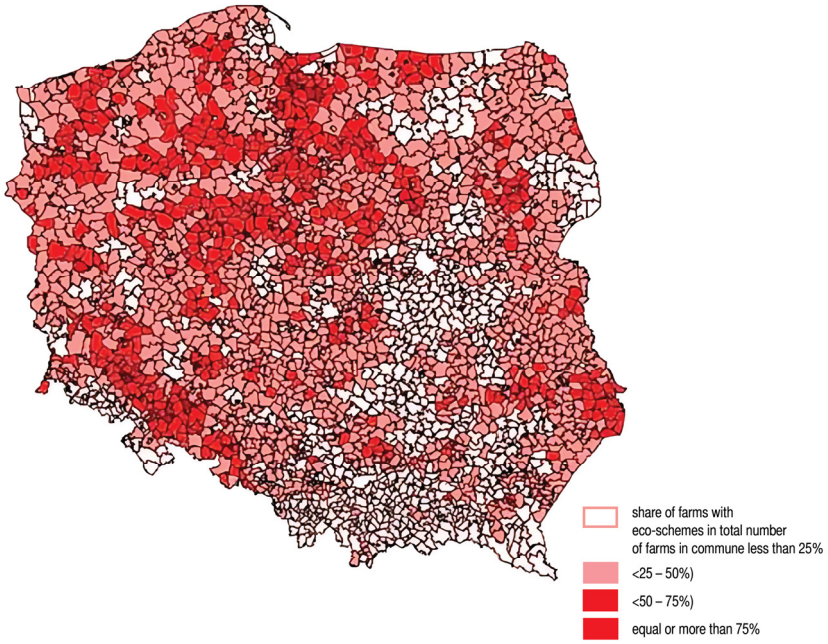


Figure 9. Share of farms implementing eco-schemes among the total number of farms in communes in Poland in 2023. Source: ARMA data for 2023.

Areas with at least 75% ANCs in the total UAA showed fewer farms participating in eco-schemes (30.6%) compared to the country as a whole. However, certain practices have been more than half implemented in the area of these communes: water retention on permanent grassland (79.3%), extensive permanent grasslands with livestock (71.8%), areas with melliferous plants (63.6%), mixing solid manure on arable land within 12 h of application (54.6%), the application of liquid manure by methods other than splashing (54.4%), winter catch crops/intercrops (52.9%), and diversified sowing structure (51.1%) (Table 4).

Table 4. UAA area covered by eco-schemes in communes with a high share of ANCs and its share in the total area covered by each practice under eco-schemes in the CAP 2023–2027 in Poland in 2023.

Specification Eco-Schemes: Eco-Scheme (1). Carbon Farming and Nutrient Management:	UAA Under Eco-Schemes in Communes with High Share of ANCs (ha)	Share in Total UAA of Eco-Scheme (%)
1.1. Extensive permanent grassland with livestock	111,282.3	**71.8**
1.2. Winter catch crops/intercrops	490,629.2	**52.9**
1.3. Fertilization plans (basic variant)	410,696.4	36.6
1.4. Fertilization plans (liming variant)	59,521.5	49.2
1.5. Diversified sowing structure	718,410.7	**51.1**
1.6. Mixing solid manure on arable land within 12 h of application	392,091.5	**54.6**
1.7. Application of liquidmanurewith methods other than splashing	326,369.9	**54.4**
1.8. Reduced tillage systems	648,294.6	31.7
1.9. Mixing straw with soil	627,663.7	32.7
Eco-scheme (2). Areas with melliferous plants	7339.6	**63.6**
Eco-scheme (3). Water retention on the permanent grassland	76,094.2	**79.3**
Eco-scheme (4). Integrated plant production	39,959.3	37.7
Eco-scheme (5). Biological plant protection	6049.7	24.5

Source: ARMA data for 2023.

In terms of the areas with a high proportion of ANCs, the practices most preferred by farmers were mixing straw into the soil, a diversified sowing structure and reduced tillage systems. It is reasonable to assume that these practices have been in use for a long time on a certain proportion of these beneficiary farms, and that the payment introduced rewards them for their previous actions aimed at preserving soil structure (or, more precisely, maintaining or increasing the level of organic matter and nutrients in the soil). There is no doubt that eco-schemes in Poland meet the environmental and climate objectives of the CAP, namely to contribute to the protection of soil resources, water, climate, animal welfare and biodiversity in agricultural production. They promote practices that translate into agricultural income by increasing soil fertility, the drought resistance of crops, rational fertilization, and crop quality. The idea is that eco-schemes should be implemented by as many farmers as possible, including in ANCs.

It should be emphasized that the practices indicated within the framework of eco-schemes have a lot to offer, enabling the agriculture in ANCs to increase soil fertility, improve the availability of nutrients to crops, use rational fertilization and, as a result, increase the quality of the products offered to consumers. Such practices are particularly necessary for Polish agriculture in these areas due to the often low natural organic matter content of arable land, and to prevent the locally occurring over-use of mineral fertilization and plant protection products.

5. Discussion

In the EU, approximately 157 million hectares of land is used for agricultural production, but this is characterized by varied natural farming conditions and often a high share of ANCs. In Poland, 58.7% of agricultural land is located in ANCs. The eco-schemes proposed by the European Commission under the CAP 2023–2027 have the potential to make agriculture more sustainable and climate-friendly. In 2023 in Poland, 1/3 of farms adopted eco-schemes. In other EU countries, the share of farms implementing eco-schemes was varied. In Spain, 75% of farms adopted eco-schemes. In Austria, 65% of farms joined eco-schemes [48,49]. Considering the increasing willingness of EU farms to implement eco-schemes, further education and the promotion of these practices among farmers is recommended. Information campaigns by agriculture-related institutions and actively participating agricultural advisory services can effectively help farms meet the access criteria and enhance the real benefits of participating in eco-schemes. In the EU, the CAP measures are increasingly aimed at providing high-quality food to consumers while reducing the negative impact of agricultural activities on the state of the natural environment, including reducing erosion and soil degradation [50–55]. Its environmental measures are becoming more solidly designed and better targeted so that agriculture is able to protect environmental public goods to the greatest extent possible. At the same time, ecosystem biodiversity is one of the most important public goods dependent on agriculture, since its existence and sustainability are a result of the quality of its agricultural practices [56–58]. In this context, much should be offered by eco-schemes practices.

Environmental measures under the CAP are the European Union's response to the degradation of the rural environment. It should be noted that these measures tend to reflect the environmental, ecological, and socio-economic problems accompanying agriculture in individual EU Member States [59]. Within environmental measures, actions related to biodiversity are of particular importance, being the most supported aspect of the EU's pro-environmental policies [60]. These measures often focus on restoring valuable natural habitats, promoting sustainable agricultural production systems, protecting soils and ensuring their appropriate use, safeguarding water resources, preserving landscape structures, and protecting local crop varieties and animal breeds. All of these areas are in accordance with the ordered model of agriculture and the concept of sustainable development [61].

Discussions on the CAP have so far mainly revolved around its design, the overall reform agenda, and the CAP's ability to achieve its objectives. For example, some authors have questioned the relevance of the proposed measures to address specific challenges [62,63], while others have pointed out the mismatch between CAP objectives and the sustainable development goals [64,65]. Various authors have also argued that the CAP lacks adequate multi-level governance, advocating for an inclusive policy-making process, which is essential for the transition to a sustainable European food system [66–68]. Farms' participation in environmental activities influences their sustainable and pro-environmental orientation [69]. These subsidies are important in shaping eco-efficiency. Picazo-Tadeo et al. [70] showed the positive impact of environmental measures on farm eco-efficiency. Gadanakis et al. [71] and Czyzewski et al. [72] also highlighted that farmers' use of these measures can improve farm eco-efficiency. It is becoming increasingly clear that there is a need for policies that are linked to regional policies that advocate for agriculture; this is in order to support local sustainable production practices. Important is the distribution of financial resources that would be able to help maintain agricultural production in a sustainable and stable manner, without causing environmental damage. It is necessary to be aware of the sustainability of agriculture, which should globally provide people with food security [73–76].

Undoubtedly, farms operating under difficult farming conditions, particularly in ANCs, that are able to adapt to their constraints will maintain their profitability in the long term. One of the most important skills in these areas is conducting agricultural production

in a way that favors the environment. The European Commission now sees great potential in implementing environmental protection through agriculture in ANCs, which currently cover 58.6% of the total agricultural area in the EU. It should be emphasized that the EC links the benefits of its support to maintaining economic viability, improving the economic situation of farms, and increasing the environmental awareness and willingness of farmers in these areas to protect the natural environment [77–80]. The support of farms in ANCs contributes to the maintenance of biodiversity, landscape diversity and attractiveness, and cultural heritage, which society regard as important public goods.

Studies have shown differences across EU countries in terms of agriculture and economically disadvantaged areas [81]. Our findings confirmed that farms located in areas where at least 75% of the total UAA is classified as an ANC made less use of eco-schemes in 2023. Considering the current situation in many agricultural product markets, in our opinion, payments to eco-schemes could be an important aspect of the farm income of beneficiaries in ANCs and influence their decisions regarding production development.

In Poland, there are some weaknesses regarding the implementation of eco-schemes. The most important of these is the varying strength of farmers' willingness to implement them on a regional basis. In the first year of CAP 2023–2027, a significant number of Polish farms did not benefit from eco-scheme subsidies. Analyzing this phenomenon from a geographic perspective, it should be emphasized that farms from regions of Poland with a better structure of farms and a higher level of agricultural development more often participated in these practices. The weaknesses observed in the implementation of the eco-scheme system in Poland are present to a large extent in areas with a poorer farm structure and economically weaker farms, where unfavorable natural conditions for farming often play a major role. The reason for this may be the insufficiency of existing regional and locally specific agricultural training campaigns to encourage farmers to implement eco-scheme practices that best fit their abilities, needs and existing farming conditions.

The ongoing negative changes in the natural environment lead us to conclude that the primary challenge for policymakers setting practices within eco-schemes is ensuring that EU agriculture has sustainable and practicable remedial solutions in this regard. The design of eco-schemes should take into account the informal signals and needs coming from the EU society, which is increasingly specifying the framework and monitoring and enforcing the effectiveness of CAP implementation in the context of environmental protection.

6. Conclusions

In the EU, including Poland, farms located in ANCs represent a large portion of the production potential of agriculture. However, farming in these areas often limits the production and economic performance of farms. This is why ANC payments have been introduced in the EU to compensate farmers for the additional costs and lost income associated with maintaining agricultural activity and, thus, vital rural communities in such areas. Subsidies to farms operating in areas with specific constraints regarding efficient agricultural production are among the longest-running instruments of the EU's Common Agricultural Policy (CAP).

This paper compares the use of eco-schemes as an important measure dedicated to agriculture, including those implemented in ANCs in Poland in the CAP 2023–2027. The hypothesis set up has not been positively verified. The analysis indicated that farms in ANCs participated slightly less frequently in eco-schemes than farms as a whole. In ANCs, the eco-schemes concerning water retention on permanent grassland and the extensive use of permanent grassland with stocking rates had the highest share in the total area of relevant eco-schemes in Poland, while biological plant protection and reduced cropping systems had the lowest.

The European Commission, through the CAP 2023–2027, attaches great importance to achieving environmental objectives in agriculture. By using direct payment funds for sustainable practices in the form of eco-schemes, it aims to strengthen incomes in agriculture while better protecting the natural environment. However, there are a number of conditions that farmers need to meet in order to access them, and there are still some concerns at this time about their impact on the economic outcomes achieved. The submitted study highlights the importance of eco-schemes in Polish agriculture in ANCs in the first year of the CAP 2023–2027. There is no doubt that in these areas, eco-schemes should play a much greater role than they do at present.

In conclusion, multifaceted and environmentally ambitious eco-schemes with attractive financing are needed in the EU in order to improve the sustainability of agriculture, especially in ANCs. At the same time, they must be constantly evaluated on farms for proper implementation to ensure that they achieve the best economic and environmental results. For the farmers who are the beneficiaries of the CAP 2023–2027 and agriculture as a sector of the economy, it is important that the principles of the current agricultural policy on eco-schemes are largely stable, and that changes in this regard are made on an evolutionary basis, without sudden turns.

In the EU, including Poland, eco-schemes should be implemented by as many farmers as possible, regardless of the size of their farm and the natural conditions under which they farm. This is because there is a need to widely involve farmers in the process of implementing eco-schemes, as this can provide further valuable insights and increase the usefulness of further research.

In future studies, it will be important to determine the impact of the application of eco-scheme practices on the economic situation of farms and the state of their environmental sustainability, as measured by the balance of organic matter, the diversification of the cropping structure, and the quality and quantity of fertilization. This research will show the direction and strength of the impact of eco-schemes on farm income and biodiversity.

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References

1. European Commission. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. The European Green Deal. COM(2019) 640 Final. 2019. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2019:640:FIN (accessed on 2 June 2024).
2. The State of the World's Land and Water Resources for Food and Agriculture 2021. Main Report. Food and Agriculture Organization of the United Nations. Rome. 2022. Available online: https://www.fao.org/land-water/solaw2021/en/ (accessed on 9 January 2025).
3. European Commisssion (2021). Communication from The Commission to the European Parliament, The European Council, The Council, The European Economic and Social Committee and the Committee of the Regions, EU Soil Strategy for 2030. Reaping the Benefits of Healthy Soils for People, Food, Nature and Climate. COM(2021) 699 Final. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52021DC0699 (accessed on 10 January 2025).

4. European Commission. Mapping and Assessment of Ecosystems and their Services: An EU Ecosystem Assessment. JRC Science for Policy Report. 2020. Available online: https://op.europa.eu/en/publication-detail/-/publication/afac1162-0f58-11eb-bc07-01aa75ed71a1/language-en (accessed on 8 December 2024).
5. European Environment Agency. The European Environment-State and Outlook 2020. Knowledge for Transition to a Sustainable Europe. 2019. Available online: https://www.eea.europa.eu/soer/2020 (accessed on 4 January 2025).
6. European Court of Auditors. Combating Desertification in the EU: A Growing Threat in Need of More Action. 2018. Available online: https://www.eca.europa.eu/en/publications?did=48393 (accessed on 4 January 2025).
7. Arias-Navarro, C.; Baritz, R.; Jones, A. The State of Soils in Europe. Publications Office of the European Union. 2024. JRC137600. Available online: https://op.europa.eu/en/publication-detail/-/publication/1f96158b-901f-11ef-a130-01aa75ed71a1/language-en (accessed on 4 January 2025).
8. Van der Zanden, E.; Verburg, P.H.; Schulp, C.J.E.; Verkerk, P.J. Trade-offs of European agricultural abandonment. *Land Use Policy* **2017**, *62*, 290–301. [CrossRef]
9. EEA 2019 Land and soils in Europe. EEA Signals. Available online: https://www.sciencedirect.com/science/article/abs/pii/S0264837716314417 (accessed on 4 January 2025).
10. Zgłobicki, W.; Karczmarczuk, K.; Baran-Zgłobicka, B. Intensity and Driving Forces of Land Abandonment in Eastern Poland. *Appl. Sci.* **2020**, *10*, 3500. [CrossRef]
11. European Commission (EC). CAP Context Indicators—2021 Update. 2021. Available online: https://agridata.ec.europa.eu/extensions/DataPortal/context_indicators.html (accessed on 10 January 2025).
12. Zimmermann, A.; Britz, W. European farm participation in agri-environmental measures. *Land Use Policy* **2016**, *50*, 214–228. [CrossRef]
13. Zieliński, M.; Jadczyszyn, J. Importance and challenges for agriculture from High Nature Value farmlands (HNVf) in Poland in the context of the provision of public goods under the European Green Deal. *Econ. Environ. Econ. Environ.* **2022**, *3*, 194–219. [CrossRef]
14. Tarolli, P.; Straffelini, E. Agriculture in Hilly and Mountainous Landscapes: Threats, Monitoring and Sustainable Management. *Geogr. Sustain.* **2020**, *1*, 70–76. [CrossRef]
15. Cooper, T.; Baldock, D.; Rayment, M.; Kuhmonen, T.; Terluin, I.; Swales, V.; Poux, X.; Zakeossian, D.; Farmer, M. *An Evaluation of the Less Favoured Area Measure in the 25 Member States of the European Union*; Institute for European Environmental Policy: Brussels, Belgium, 2006.
16. Cagliero, R.; Vassallo, M.; Pierangeli, F.; Pupo D'Andrea, M.R.; Monteleone, A.; Camaioni, B.; Tarangioli, S. The Common Agricultural Policy 2023–2027: How Member States Implement the New Delivery Model? *Ital. Rev. Agric. Econ.* **2023**, *78*, 49–66. [CrossRef]
17. European Parliament 2023. European Parliamentary Research Service. Guide to EU Funding 2023 edition. Available online: https://www.europarl.europa.eu/thinktank/en/document/EPRS_STU(2023)747110 (accessed on 15 December 2024).
18. European Commission. Approved 28 CAP Strategic Plans (2023–2027). 2023. Available online: https://agriculture.ec.europa.eu/document/download/7b3a0485-c335-4e1b-a53a-9fe3733ca48f_en?filename=approved-28-cap-strategic-plans-2023-27.pdf (accessed on 11 January 2025).
19. Official Journal of the European Union. Regulation (EU) 2021/2115 of the European Parliament and of the Council of 2 December 2021 Establishing Rules on Support for Strategic Plans to be Drawn up by Member States Under the Common Agricultural Policy (CAP Strategic Plans) and Financed by the European Agricultural Guarantee Fund (EAGF) and by the European Agricultural Fund for Rural Development (EAFRD) and Repealing Regulations (EU) No 1305/2013 and (EU) No 1307/2013. 2021. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021R2115 (accessed on 11 January 2025).
20. Feindt, P.; Grohmann, P.; Hager, A. The CAP post-2020 reform and the EU budget process. In *EU Policymaking at a Crossroads. Negotiating the 2021–2027 Budget*; Munch, S., Heinelt, H., Eds.; Edward Edgar Publishing: Cheltenham, UK, 2022.
21. Castillo-Diaz, F.J.; Belmonte-Urena, L.J.; Alvarez-Rodriguez, J.F.; Cachao-Ferre, F. The Role of Sustainability and Circural Economy in Europe's Common Agricultural Policy. In *Environmentally Sustainable Production. Research for Sustainable Development*; Valls Martinez, M.A., Santos-Jaen, J.M., Eds.; Springer: Cham, Switzerland, 2024.
22. European Commission. *List of Potential Agricultural Practices that Eco-Schemes Could Support*; European Commission: Brussels, Belgium, 2021.
23. Latacz-Lohmann, U.; Termansen, M.; Nguyen, C. *The New Eco-Schemes: Navigating a Narrow Fairway, EuroChoices*; Wiley: Hoboken, NJ, USA, 2022; Volume 21, pp. 4–10. ISSN 1746-692X. [CrossRef]
24. Pe'er, G.; Bonn, A.; Bruelheide, H.; Dieker, P.; Eisenhauer, N.; Feindt, P.; Hagedorn, G.; Hansurgens, B.; Herzon, I.; Lomba, A.; et al. Action needed for the EU Common Agricultural Policy to address sustainability challenges. *People Nat.* **2020**, *2*, 305–316. [CrossRef]
25. Pe'er, G.; Finn, J.A.; Diaz, M.; Brikenstock, M.; Lakner, S.; Röder, N. How can the European Common Agricultural Policy helphalt biodiversity loss? Recommendations by over 300 experts. *Conserv. Lett.* **2022**, *15*, e12901. [CrossRef]

26. Hlavsa, T.; Spicka, J.; Stolbova, M.; Hlouskova, Z. Statistical analysis of economic viability of farms operating in Czech areas facing natural constraints. *Agric. Econ.* **2020**, *66*, 193–202.
27. Communication from The Commission to the European Parliament, The European Council, The Council, The European Economic and Social Committee and the Committee of the Regions. EU Biodiversity Strategy for 2030. Bringing Nature Back into our Lives. COM (2020) 380 Final. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52020DC0380 (accessed on 16 December 2024).
28. Communication from The Commission to the European Parliament, The European Council, The Council, The European Economic and Social Committee and the Committee of the Regions. A Farm to Fork Strategy for a Fair, Healthy and Environmentally-Friendly Food System. COM (2020) 381 Final. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52020DC0381 (accessed on 16 December 2024).
29. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. Forging a Climate—Resilient Europe_the New EU Strategy on Adaptation to Climate Change, COM (2021) 82 Final. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2021:82:FIN (accessed on 16 December 2024).
30. Papić, R. Rural development policy on areas with natural constraints in the Republic of Serbia. *Ekon. Poljopr.* **2022**, *69*, 75–89. [CrossRef]
31. Clough, Y.; Kirchweger, S.; Kantelhardt, J. Field sizes and the future of farmland biodiversity in European landscapes. 2020. Available online: https://conbio.onlinelibrary.wiley.com/doi/epdf/10.1111/conl.12752 (accessed on 4 June 2024).
32. Kazakova-Mateva, Y. Effects of Less Favoured Areas support in territories with natural constraints. *Trakia J. Sci.* **2017**, *15*, 29–35. [CrossRef]
33. Plieninger, T.; Gaertner, M.; Hui, C.; Huntsinger, L. Does land abandonment decrease species richness and abundance of plants and animals in Mediterranean pastures, arable lands and permanent croplands? *Environ. Evid.* **2013**, *2*, 3. [CrossRef]
34. Stoate, C.; Baldi, A.; Beja, P.; Boatman, N.D.; Herzon, I.; van Doorn, A.; de Snoo, G.R.; Rakosy, L.; Ramwell, C. Ecological impacts of early 21st century agricultural change in Europe—A review. *J. Environ. Manag.* **2009**, *91*, 22–46. [CrossRef] [PubMed]
35. Redlichova, E.; Blažková, I.; Chmelíková, G.; Vinohradský, K. Links between farm size, location and productivity of farms in the Czech Republic. *Eur. Countrys.* **2023**, *15*, 508–524. [CrossRef]
36. Zieliński, M.; Jadczyszyn, J.; Sobierajewska, J. Predispositions and challenges of agriculture from areas particularly facing natural or other specific constraints in Poland in the context of providing environmental public goods under EU policy. *Agric. Econ.* **2023**, *69*, 309–320. [CrossRef]
37. Wąs, A.; Malak-Rawlikowska, A.; Zavalloni, M.; Viaggi, D.; Kobus, P.; Sulewski, P. In search of factors determining the participation of farmers in agri-environmental schemes—Does only money matter in Poland? *Land Use Policy* **2021**, *101*, 105190. [CrossRef]
38. European Commission (EC). Areas with Natural Constraints. Overview and Socio-Economic and Environmental Features of Farming in ANC Areas Based on FADN Data. 2023. Available online: https://agriculture.ec.europa.eu/document/download/586ba067-4ce9-4afe-8139-719253ed0f45_en?filename=analytical-brief-1-anc-brief_en.pdf (accessed on 15 December 2024).
39. Meredith, S.; Hart, K. CAP 2021–2027: Using the Eco-Scheme to Maximise Environmental and Climate Benefits. 2019. Available online: https://www.organicseurope.bio/content/uploads/2020/06/ifoam_eu_eco-scheme_report_final.pdf (accessed on 15 December 2024).
40. Lampkin, N.; Stolze, M.; Meredith, S.; de Porras, M.; Haller, L.; Mészáros, D. Using Eco-Schemes in the New CAP: A Guide for Managing Authorities. 2020. Available online: https://www.organicseurope.bio/content/uploads/2020/06/ifoam-eco-schemes-web_compressed-1.pdf?dd (accessed on 6 January 2025).
41. Pilvere, I.; Nipers, A.; Pilvere, A. Evaluation of the European Green Deal Policy in the Context of Agricultural Support Payments in Latvia. *Agriculture* **2022**, *12*, 2028. [CrossRef]
42. Donham, J.; Wezel, A.; Migliorini, P. Improving Eco-Schemes in the Lighnt of Agroecology. AE4EU. 2022. Available online: https://www.agroecology-europe.org/wp-content/uploads/2022/02/Improving-eco-schemes-in-the-light-of-agroecology-Policy-Brief-Feb-2022-AE4EU.pdf (accessed on 9 January 2025).
43. Tataridas, A.; Kanatas, P.; Chatzigeorgiou, A.; Zannopoulos, S.; Travlos, I. Sustainable Crop and Weed Management in the Era of the EU Green Deal: A Survival Guide. *Agronomy* **2022**, *12*, 589. [CrossRef]
44. Sarvia, F.; Xausa, E.; De Petris, S.; Cantamessa, G.; Borgogno-Mondino, E.A. Possible Role of Copernicus Sentinel-2 Data to Support Common Agricultural Policy Controls in Agriculture. *Agronomy* **2021**, *11*, 110. [CrossRef]
45. Zieliński, M.; Koza, P.; Łopatka, A. Agriculture from Areas Facing Natural or Other Specific Constraints (ANCs) in Poland, Its Characteristics, Directions of Changes and Challenges in the Context of the European Green Deal. *Sustainability* **2022**, *14*, 11828. [CrossRef]
46. Józwiak, W.; Sobierajewska, J.; Zieliński, M.; Ziętara, W. The Level of Labour Profitability and Development Opportunities of Farms in Poland. *Probl. Agric. Econ.* **2019**, *2*, 28–42. [CrossRef]

47. Zieliński, M.; Gołębiewska, B.; Adamski, M.; Sobierajewska, J.; Tyburski, J. Adaptation of eco-schemes to Polish agriculture in the first year of the EU CAP 2023–2027. *Econ. Environ.* **2024**, *89*, 817. [CrossRef]
48. Available online: https://eu-cap-network.ec.europa.eu/sites/default/files/publications/2024-01/report-1-tg-ecoschemes.pdf (accessed on 11 December 2024).
49. Weber, T.M. Eco-schemes—First Year of Implementation in Austria and First Experiences. 2023. Available online: https://cld.pt/dl/download/2bc028bf-20e0-4a95-87a1-51afbfc96107/23jun06CI-RegimesEcol%C3%B3gicos_nos_EstadosMembros/Eco-schemes_LKO_%C3%81ustria-Thomas%20Weber.pdf?download=true (accessed on 29 December 2024).
50. Panagos, P.; Borrelli, P.; Poesen, J.; Ballabio, C.; Lugato, E.; Meusburger, K.; Montanarella, L.; Alewell, C. A new assessment of soil loss from water erosion in Europe. *Environ. Sci. Policy* **2015**, *54*, 438–447.
51. Cerdà, A.; Rodrigo-Comino, J.; Novara, A.; Brevik, E.C.; Vaezi, A.R.; Pulido, M.; Giménez-Morera, A.; Keesstra, S.D. Long-term effects of precipitation-induced agricultural land abandonment on soil erosion in the western Mediterranean basin. *Prog. Phys. Geogr. Earth Environ.* **2018**, *42*, 202–219.
52. Sarkar, D.; Kar, S.K.; Chattopadhyay, A.; Shikha, A.; Rakshit, A.; Tripathi, V.K.; Dubey, P.K.; Abhilash, P.C. Sustainable low input agriculture: A viable climate smart option for increasing food production in a warming world. *Ecol. Ind.* **2020**, *115*, 106412.
53. Pijl, A.; Reuter, L.E.H.; Quarella, E.; Vogel, T.A.; Tarolli, P. GIS-based soil erosion modelling in different viticulture practices on steep slopes. *Catena* **2020**, *193*, 104604.
54. Schütte, E.; Plaas, J.A.; Gómez, G.G. Cost-effectiveness of erosion control with cover crops in European vineyards considering environmental costs. *Environ. Dev.* **2020**, *35*, 100521.
55. O'Rourke, E.; Kramm, N. High Nature Value (HNV) farming and the management of upland diversity. A review. *Eur. Countrys.* **2012**, *2*, 116–133. [CrossRef]
56. Díaz, M.; Concepción, E.D. Enhancing the effectiveness of CAP greening as a conservation tool: A call for regional targeting with landscape constraints. *Curr. Landsc. Ecol. Rep.* **2016**, *1*, 168–177. [CrossRef]
57. Gatto, P.; Mozzato, D.; Defrancesco, E. Analysis of the role of factors influencing farmers' decision to continue agri-environmental programmes from a temporal perspective. *Environ. Sci. Policy* **2019**, *92*, 237–244.
58. Tyllianakis, E.; Martin-Ortega, J. Agri-environmental programmes for biodiversity and conservation: Why we are still not "hitting the right buttons". *Land Use Policy* **2021**, *109*, 105620. [CrossRef]
59. Duer, I. Agri-environmental programmes as an instrument for environmental resources protection in the Common Agricultural Policy of the European Union. Studies & Reports IUNG-PIB. Available online: https://bc.iung.pl/server/api/core/bitstreams/86fe31ca-f698-4f3b-a677-379a2c19cc49/content (accessed on 29 December 2024).
60. Hadyńska, A.; Hadyński, J. Directions and prospects for the development of agri-environmental programmes in the EU, Annals of the Polish Association of Agricultural and Agribusiness Economists 2005. Available online: https://bazekon.uek.krakow.pl/rekord/101464031 (accessed on 29 December 2024).
61. Kruszyński, M. Pro-environmental measures as an instrument of the Common Agricultural Policy of the European Union. *Agric. Advis. Issues* **2023**, *4*, 26–39.
62. Lovec, M.; Šumrada, T.; Erjavec, E. New CAP Delivery Model, Old Issues. *Intereconomics* **2020**, *55*, 112–119.
63. Navarro, A.; Lopez-Bao, V.J. EU Agricultural Policy Still Not Green. *Nat. Sustain.* **2019**, *2*, 990.
64. Pe'er, G.; Zinngrebe, Y.; Moreira, F.; Sirami, C.; Schindler, S.; Müller, R.; Bontzorlos, V.; Clough, D.; Bezak, P.; Lakner, S.A. Greener Path for the EU Common Agricultural Policy. *Science* **2019**, *365*, 449–451.
65. Scown, M.; Brady, M.V.; Nicholas, A.K. Billions in Misspent EU Agricultural Subsidies Could Support the Sustainable Development Goals. *One Earth* **2020**, *3*, 137–150.
66. Galli, F.; Prosperi, P.; Favilli, E.; D'Amico, S.; Bartolini, F.; Brunori, G. How Can Policy Processes Remove Barriers to Sustainable Food Systems in Europe? Contributing to a Policy Framework for Agri-Food Transitions. *Food Policy* **2020**, *96*, 101871.
67. Kugelberg, S.; Bartolini, F.; Kanter, R.D.; Milford, B.A.; Pira, K.; Sanz-Cobena, A.; Leip, A. Implications of a Food System Approach for Policy Agenda Setting Design. *Glob. Food Secur.* **2021**, *28*, 100451.
68. Recanati, F.; Maughan, C.; Pedrotti, M.; Dembska, K.; Antonelli, M. Assessing the Role of CAP for more Sustainable and Healthier Food Systems in Europe: A Literature Review. *Sci. Total Environ.* **2019**, *653*, 908–919.
69. Bonfiglio, A.; Arzeni, A.; Bodini, A. Assessing the eco-efficiency of farms in rural areas. *Agric. Syst. V* **2017**, *151*, 114–125.
70. Picazo-Tadeo, A.; Beltrán-Esteve, M.; Gómez-Limón, J. Evaluation of ecological effectiveness using directional distance functions. *Eur. J. Oper. Res.* **2012**, *220*, 798–809. [CrossRef]
71. Gadanakis, Y.; Bennett, R.; Park, J.; Areal, F. Evaluating the sustainable intensification of arable farms. *J. Environ. Manag.* **2015**, *150*, 288–298. [CrossRef] [PubMed]
72. Czyżewski, B.; Trojanek, R.; Dzikuć, M.; Czyżewski, A. Cost-effectiveness of the common agricultural policy and environmental policy in country districts: Spatial spillovers effects of pollution, bio-uniformity and green schemes in Poland. *Sci. Total Environ.* **2020**, 138254. [CrossRef] [PubMed]
73. Liu, M.; Chen, X.; Jiao, Y. Sustainable Agriculture: Theories, Methods, Practices and Policies. *Agriculture* **2024**, *14*, 473. [CrossRef]

74. Kowalczyk, S.; Zolotnytska, Y. Sustainability of agriculture and rural areas in regional terms. *Econ. Environ.* **2024**, *89*, 773. [CrossRef]
75. Kalinowska, B.; Bórawski, P.; Bełdycka-Bórawska, A.; Klepacki, B.; Perkowska, A.; Rokicki, T. Sustainable Development of Agriculture in Member States of the European Union. *Sustainability* **2022**, *14*, 4184. [CrossRef]
76. Guth, M.; Smędzik-Ambroży, K.; Czyżewski, B.; Stępień, S. The Economic Sustainability of Farms under Common Agricultural Policy in the European Union Countries. *Agriculture* **2020**, *10*, 34. [CrossRef]
77. Hloušková, Z.; Lekešová, M.; Prajerová, A.; Doucha, T. Assessing the Economic Viability of Agricultural Holdings with the Inclusion of Opportunity Costs. *Sustainability* **2022**, *14*, 15087. [CrossRef]
78. Ragosta, M.; Daniele, G.; Imbrenda, V.; Coluzzi, R.; D'Emilio, M.; Lanfredi, M.; Matarazzo, N. Land Transformations in Irpinia (Southern Italy): A Tale on the Socio-Economic Dynamics Acting in a Marginal Area of the Mediterranean Europe. *Sustainability* **2024**, *16*, 8724. [CrossRef]
79. Soulis, K.X.; Kalivas, D.P.; Apostolopoulos, C. Delimitation of Agricultural Areas with Natural Constraints in Greece: Assessment of the Dryness Climatic Criterion Using Geostatistics. *Agronomy* **2018**, *8*, 161. [CrossRef]
80. Klima, K.; Kliszcz, A.; Puła, J.; Lepiarczyk, A. Yield and Profitability of Crop Production in Mountain Less Favoured Areas. *Agronomy* **2020**, *10*, 700. [CrossRef]
81. The State of Soils in Europe. Fully Evidenced, Spatially Organised Assessment of the Pressures Driving Soil Degradation. 2024. European Comission, Eu-ropean Environmental Agency. Available online: https://publications.jrc.ec.europa.eu/repository/handle/JRC137600 (accessed on 3 January 2025).

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Creating an Alternative Governance for Phosphorus Circularity Through Framings That Strengthen Intersectoral Policy Coherence in the EU: Constraints and Implementation Possibilities

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Abstract: Phosphorus' availability and pricing is critical for the entire food system. Transformative phosphorus governance is required to reduce the European Union's fertiliser vulnerability. At the same time, the EU's governance approach is constrained by multiple problem definitions and missing salient framings that could make phosphorus recovery a priority of the EU's decision-making agenda. The article addresses this policy gap by gathering and discussing different institutional and stakeholder framings that could inform a transition to a transformed phosphorus governance. We combine triangulated methods (framing as an analytical heuristic, semi-structured expert interviews, document analysis, and conference observations) with Kingdon's three streams of agenda-setting as a conceptual framework to identify alternative intersectoral framings of phosphorus sustainability. Our findings suggest that the window of opportunity filled by the EU's Fertiliser Affordability Communication supports a decarbonisation pathway that fails to emphasise the potential of emergent framings supporting phosphorus recovery. We analyse these framings and suggest that a new window of opportunity for their elevation on the EU's decision-making agenda is opening with the inauguration of a new European Commission. We propose five alternatives that apply powerful spillover framings to implement phosphorus governance that is synchronous with the commission's sectoral priorities. We believe that an extension of the EU's current environmental policy along these pathways can potentially contribute to phosphorus sustainability.

Keywords: framing; phosphorus; renewable; circular; strategic; transformation; governance

1. Introduction

The global phosphorus challenge is framed increasingly through the exhaustibility and discrete availability of phosphate rock (85% of which is concentrated in just five countries), the embeddedness of 72% of all phosphorus in animal feed and livestock rearing, soil phosphorus deficits at 30–32%, chemical fertiliser overapplication at 30–40% leaching into water bodies and triggering toxic eutrophication, and its persistently low recycling rates [1–4].

Around 80% of phosphorus is used in food production [5], and 80% of that amount is lost between crop farming and food consumption [6]. Despite phosphorus' non-

substitutability for food security [7], its governance does not reflect the increasing demand for Lithium Iron Phosphate (LFP) batteries and microchips [8–10]. Global trade has improved phosphorus' accessibility, but is increasingly contributing to its wasteful use and susceptibility to price shocks, making a transition to local crop–livestock system integration and accelerated nutrient recycling a necessity [11,12]. Nutrient recovery processes are also important for advancing sustainability, as they can offset 50–70% of phosphorus lost along the supply chain [13]. In addition, the projected 0.6–1.5% increase in fertiliser demand cannot be met solely by decarbonising fertilisers' chemical synthesis [13].

Neither critical advances in circularity nor phasing out carbon-intensive products and industries rest at the centre of the transition to phosphorus sustainability. Instead, phosphorus governance is trapped in technocratic recycling targets that receive little political attention [14]. Few demonstration plants in the EU showcase the potential of recovery technologies [15], regardless of estimations that 15–17% of phosphate rock can be substituted with recycling [16,17]. While the EU cannot overcome its import reliance on mined phosphate rock (84%) (the EU has phosphate mines in Sokli and Siilinjärvi, Finland, and new mines with significant reserves (70bn tons) were found in south Norway (Bjerkreim–Sokndal); however, currently there is no evidence regarding their economic feasibility) and processed phosphorus (100%) through its substitution with other elements, it can achieve better resilience to market shocks by exploiting and recycling underutilised phosphorus streams [12,18]. The problem is that phosphorus management has been largely left to markets [19] and the EU formally governs the element through obligations for a 20% reduction in chemical fertiliser application and a 50% increased fertiliser use efficiency [20–23]. These targets have the potential to reduce the eutrophication caused by phosphorus leaching and are echoed by a range of United Nations biodiversity and chemical governance frameworks [24].

However, these top-down regulatory approaches suffer from poor enforceability and do not reflect inefficiencies across the phosphorus supply chain, which would remain unregulated [22], as phosphorus extraction, fertiliser production, animal feed growing, livestock rearing, and food consumption may happen outside the EU [25]. Key challenges such as climate change and the scramble for obtaining funding for decarbonisation also remain unaccounted for [26–29]. These approaches do not direct efforts towards advanced chemical recycling or nature-based solutions. Such targets allow only for small technical changes and leave the strategic direction of phosphorus governance ambiguous [14,30–33]. In contrast, the governance of nitrogen has benefitted from nitrogen oxide's recognisable framing as an acidifying greenhouse gas that damages public health, which has appealed to high-level politics and driven substantial research into its climate effects [34–37]. Although phosphorus acid is produced with sulfuric acid derived from the processing of fossil fuels [38], there is more public awareness of nitrogen, due to the direct usage of natural gas in its synthesis [35,39].

The EU's record of framing entrepreneurship in environmental policy could be explained through the usage of market mechanisms that encourage reforms in exporting counterparties [40–42]. For example, the inclusion of fertilisers in the EU Carbon Border Adjustment Mechanism (CBAM) could trigger not only emission accounting in companies, but also the adoption of emission taxation or allowances' trading in third countries [43]. Innovative patterns of governance can also be promoted in multilateral formats such as the G7 and G20 [44,45]. Although the EU has a modest influence in reciprocating its internal framings in other multilateral organisations, improving its internal policy coherence is key to consolidate these efforts [46]. Multiple policy sectors in the EU have relevance to phosphorus, and their objectives can serve as the backbone for a more coherent phosphorus governance that makes the best use of the EU's existing instruments (see Figure 1).

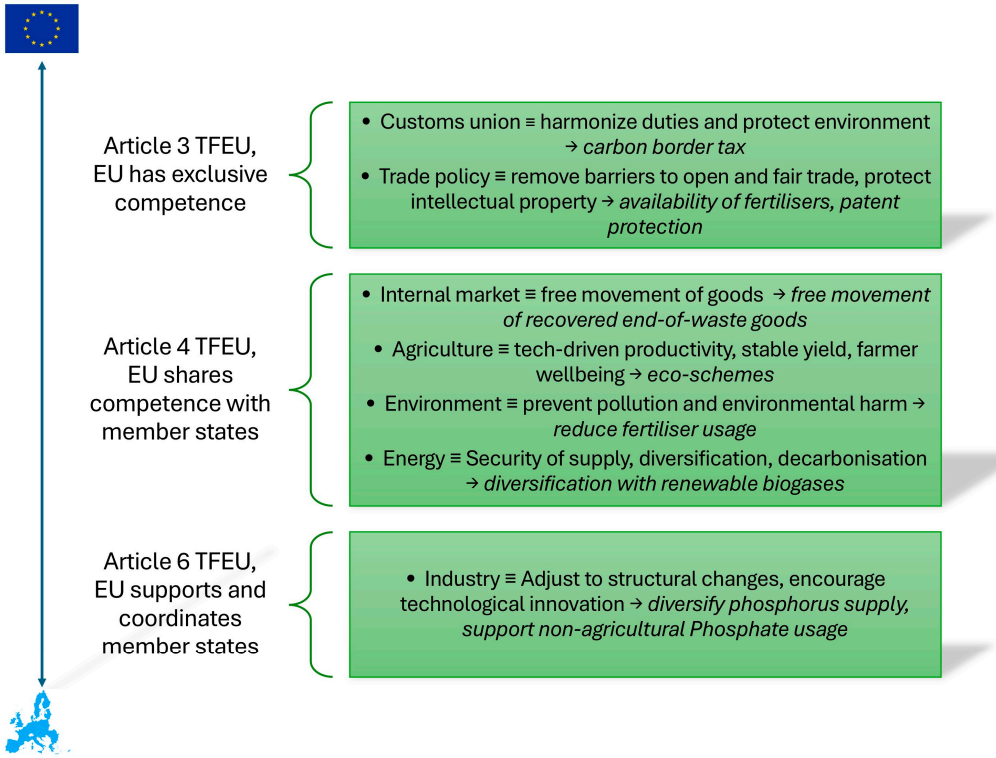


Figure 1. Division of competencies in the EU, sectoral policy objectives, and relevance to phosphorus. The arrow represents the spectrum between exclusive legislative competence exercised by the EU as a federal entity in the sectors above (depicted by the EU flag) and its complementary legislative competence exercised in the sectors below (depicted by the EU map).

Addressing this policy gap by reformulating the existing phosphorus framings may have ramifications for the holistic understanding of the global phosphorus challenge. In this paper, we bridge a research gap by gathering and discussing the alternative institutional and stakeholder perspectives across EU policy sectors to inform this process of governance transformation.

We do so by asking the following questions:

1. What intersectoral framings can emerge to inform a more coherent phosphorus governance?
2. What dynamics and vested interests in the EU constrain the advancement of these framings on the political agenda?

We answer these questions by (1) discussing the related institutional framings and those elevated by stakeholders as feedback towards the existing agenda in the EU and (2) identifying powerful spillover framings that can trigger intersectoral learning through participant observation at stakeholder conferences and analysing the reasons for their limited potential.

2. Conceptual Framework

Traditionally, governance is seen as the formal and informal interaction between institutions steering "hybrid and multi-jurisdictional" phenomena [47] and stakeholders shaping institutional designs and objectives [48]. Governance innovation may contribute to the creation of new markets to alter technology trajectories and point the way forward through times of political uncertainties via borrowing or extending a proven principle in a new policy field, context, or jurisdiction [49]. For example, EU missions were conceived to address the failures of the economic growth paradigm and redirect growth and technologi-

cal innovation towards solving societal challenges, such as restoring soils and adapting to climate change [50–52].

Due to the frictions between the regulatory momentum propagated by the European Commission and member states' struggle to constrain this process, in the EU, this innovation process often happens through softer modes of governance based on the voluntary adoption of guidelines, benchmarks, and best practices [53]. It typically involves modes of multi-level negotiation, which allow transformative governance coalitions to form, and subsequently change, the direction of policy [54]. Still, this complex multi-level governance process often results in piecemeal solutions.

Since experimental evidence alone is unlikely to solve the global phosphorus challenge [14], we employ framings as an analytical heuristic device to explore the shifting and often unknown definitions of complex problems [55]. Framing is a socially constructed interpretation of an occurrence [56]. Framing analysis explores how intentional formulations of choice problems can shift an actor's preferences [57]. Framing has inspired strategies for alignment through the amplification of beliefs or extension of objectives [58], and is the device that defines a problem, its causality, and remedies [59]. In public policy, competing framings are supported by sponsors and serve as prototypes that inform the reframing of an existing controversy [60]. The reframing dialogue may involve strategies such as incorporating inferior issues and accommodating differences by excluding incompatibilities [61]. In the EU, decision frames are usually a result of consensual decision-making that presents policy options neutrally; however, institutions or actors may be interested in emphasising a policy direction [62,63]. The framing of policy choices can therefore exemplify the vested economic interests of stakeholders interested in capturing the institutional agenda [64–66]. Beyond embellishing, incumbent stakeholders may also be interested in employing framing as a heuristic device to obscure inconvenient aspects of a problem.

To summarise, we understand framings as the core objectives of a discourse that defends a policy option [60], and an embodiment of power relations [67]. We also take note of existing critiques of framing theory and focus on using a particular unit of analysis (EU Laws), as well as exposure to more than a single experimental context [68]. Since socio-political processes are dynamic and may involve the conscious and strategic unfolding of frames or exhibit transformation weaknesses over time, we also investigate the entirety of the EU's legislative programme, the Green New Deal [69]. To further improve reproducibility, we do not explore the idiosyncratic effects of legal framings in persuading and directing the masses. Instead, we analyse the limitations of existing policy objectives in the EU and propose reframings derived from relevant strategies and laws [61].

We base our analysis on Kingdon's three streams theory [70], a well-established concept for researching agenda-setting, which has not been previously used in phosphorus research. The concept suggests that the reframing of the decision-making agenda is contingent upon the identification of circumstances as problems that require attention, as well as policy entrepreneurs' alignment across the following three streams: problems, policies, and politics:

1. Problems: There are many alternative problem definitions developed outside of government that compete to attract attention and become recognisable issues [70,71]. Problems may be constructed through frames that suit the governance actors' preference for solutions, which are proposed at high-profile focusing events or after a crisis has drawn the attention of policymakers [72]. Frames may be supported by negative feedback on existing policy (e.g., shifting effects) or indicators [73];
2. Policies: Solutions to the problem such as policy recommendations may be based on feedback on existing policy and are diffused in a discussion between authoritative sponsors and the policy officials who evaluate them [70]. In the case of the EU, the

EU Commission is a gatekeeper, which provides technically feasible solutions and the routes for policy review [74,75]. In its action, it can be affected by foreign policy or competing priorities among different directorates [76,77]. The sponsors are expert policy communities with sufficient resources, access to, and understanding of EU policy making [78,79];

3. Politics: The influence of government agendas is realised through organised advocacy by powerful interest groups, significant swings in national mood, or alterations to the composition of the government [70]. In the EU, there is oftentimes no common European position on policy choices across member states [74,78]. The biggest opportunity for influence lies in the election of a new European Parliament and new office of the Commission, but it may include Council Presidencies, parliaments' right to legislative initiatives, political resolutions by the EU Parliament, or prime ministers, as well as political spillovers [74,75,78,79].

Framing can be used as a manipulation tactic to advance a problem formulation that sets out a policy solution [80–82]. While some early conceptual debates differentiate between an epistemic community of recognised experts and an advocacy coalition comprising a variety of stakeholders, more recent perspectives suggest the definition expert policy entrepreneurs, who work across the three streams to bring an issue to the attention of high-level officials [70,79,83,84]. Based on the above, we developed the framework illustrated in Figure 2.

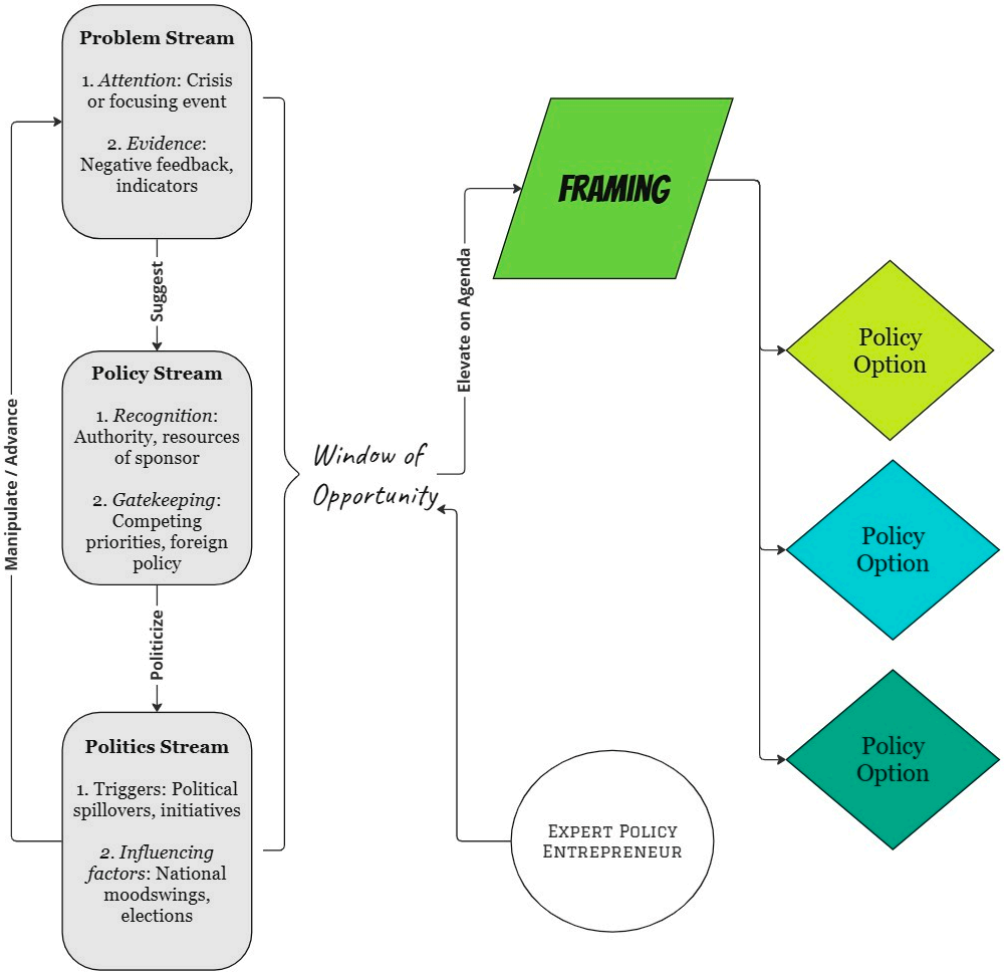


Figure 2. The interactions between the three streams that produce a policy window and a representation of how policy entrepreneurs elevate framings that suggest policy options.

Ontologically, we take a critical realist stance over the intractable nature of reality that can be described by a theory, but that requires critical examination to generate knowledge. Epistemologically, due to the siloed understanding of the phosphorus problem, we object to the current realist and positivist understanding of and focus on the subjective and pluralist reality of the object of study—phosphorus framings as interpretive devices embraced by relevant actors based on their interests, backgrounds, and worldviews [85,86]. We use the conceptual framework to engage in critical theoretical inquiry into existing assumptions defined by hegemonic power relations and advocate for a new framing [87,88].

3. Methodology

3.1. Research Method

To address the research questions and to build upon previous conceptual groundwork in phosphorus framing for governance change [14], we carried out thirty semi-structured interviews with phosphorus experts. To analyse the data, firstly, we applied inductive coding to interview transcripts to identify framings in the feedback provided by stakeholders (see Figure 3).

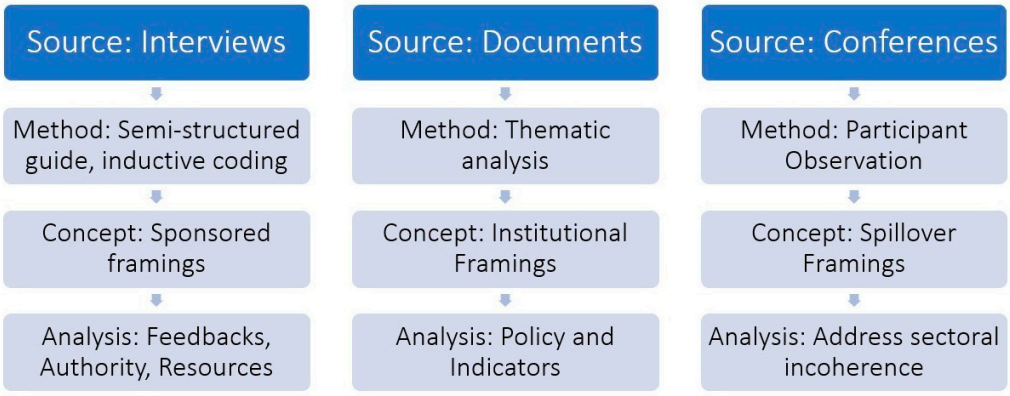


Figure 3. Triangulation of empirical sources and methods.

Secondly, we combined these data with a thematic document analysis of relevant EU strategies and laws aimed at identifying institutional framings in the EU that are applicable to phosphorus [89]. We then categorised and labelled the framings shaped by stakeholders of pphosphorus governance, on the one hand, and relevant EU institutional framings, on the other hand, into general framings that can speak to high-level policymakers and, subsequently, synthesised them into recognisable, overarching meta-framings [69,70].

Thirdly, we triangulated the method and data sources by applying participant observation at three stakeholder conferences, through which we identified framings that could induce political spillover effects formally shaped by the vertical division of powers in the EU and open a window for policy change based on learning across sectoral policies [90,91].

Applying these spillover framings to the sponsored and institutional framings allows us to employ the definition of institutional innovations as anticipating uncertainty by borrowing or extending a proven principle into a new policy field [49]. Thus, we are also able to address inter-sectoral controversies rooted in variable policy design [86,92]. Our expectation is that reframing towards more coherent governance will make phosphorus a recognisable problem and provide new advocacy tools to stakeholders working in environmental policy.

We answer the first research question by analysing the authority and access to resources of sponsored framings providing feedback on existing policy and indicators, and which spillover framings may trigger the opening of an intersectoral policy window of opportunity [14,70,91].

We answer the second research question by analysing which framings with substantial authority and resources have influenced the institutional agenda, and whether these advance a problem definition that serves vested interests. Manipulative definitions may include conceptual recycling of circularity [93], a linear fossil economy [94], defending existing structures [95], or dealing with crises through the allocation of capital to their expert community [96].

Lastly, to apply the conceptual framework, we identify the possibility to open a policy window that can address the EU's vulnerability to external shocks by elevating long-term, capital-redistributive, experimentation-oriented framings that can induce radical change in phosphorus governance through intersectoral learning [12,91,96].

3.2. Data Collection

The qualitative empirical data were collected in 2022–2023 in three phases:

a. *Semi-structured interviews*: This sponsorship scoping phase [97–100] consisted of 30 in-depth interviews with experts based on an interview guide focusing on institutional fragmentation, actors' visions for a circular phosphorus economy, and potential institutional innovations (see Table 1 and Annex I, Appendix A). The experts were recruited at the European Sustainable Phosphorus Conference (ESPC4), the biannual landmark event of the European Sustainable Phosphorus Platform (ESPP), which drives the regulatory debate on phosphorus in the EU.

b. *Document Analysis*: The European Commission search engine was used to generate a scoping snapshot of phosphorus-related documents in May 2023 through the search word: "phosp*". To improve the transferability of the findings [101], the focus of the analysis was shifted to strategies and laws of relevance to the recovery and the end-uses of phosphorus (see Figure 4 and Annex II in Supplementary Materials) and the EurLex/EU Parliaments' Legislative Train, while the search strings were expanded to "phosp*, fertiliser, nutrient, resource". The political objectives of each document were extracted while paying attention to the themes that emerged (i.e., energy and climate).

c. *Participant Observation*: Besides observations of the industry at the ESPC4, we made further non-participant observations of policymakers at two annual stakeholder conferences organised by the EU: Green Week 2023 and Sustainable Energy Week 2023. Ultimately, we transcribed the collected field notes into observed spillover framings [102] (See Annex II).

3.3. Data Analysis

The analysis focused firstly on the extraction of framings from the empirical qualitative data. This was carried out inductively for the collected interviews and resulted in "actors, barriers and innovations" as codes that informed the sponsored framings. The key words and core objectives of EU strategies and laws were used to identify the policies and indicators and derive institutional framings. Lastly, field notes from conferences were organised into spillover framings and supplemented with online quotes provided by the organisers. These three framing types were organised into general framings that can speak to high-level policymakers and grouped thematically into identifiable meta-framings.

Table 1. Interview participants.

Nr.	Role and Occupation	Organisation Type	Level	Sector
1	Circular Economy Director	Company	European	Fertilisers
2	Sustainability Director	Company	European	Waste Management
3	Policy Officer in the Biogas Industry	Association	European	Biogas
4	Anonymized	SME	National	Nanomaterials
5	Anonymized	SME	European	Fertilisers and Biogas
6	Head of Fertiliser Department	Association	National	Building Materials and Steel Slag
7	Scientific Manager	Consultancy	National	Fertilisers
8	Project Manager	Association	Macro-region	Agriculture and Environment
9	Anonymized	Research	National	AI
10	Anonymized	Research	National	Agriculture and Waste
11	Anonymized	EU Institution	European	Fertilisers
12	Director General	Association	European	Fertilisers
13	Anonymized	Association	Macro-region	Environment
14	Researcher	Research	National	Agriculture
15	Anonymized	Association	National	Fertilisers
16	Senior Policy Officer, EurEau	Association	European	Water Utilities
17	Anonymized	Company	European	Remote Sensing
18	Anonymized	Ministry	National	Institutions
19	Anonymized	Consultancy	European	Systems and Biobased Innovation
20	Anonymized	Company	National	Vivianite and Batteries
21	Anonymized	Platform	National	Phosphorus
22	Manager	Platform	National	Phosphorus
23	Project Manager	Tech Centre	National	Water Innovation
24	Natural Resources Associate, Systemiq	Consultancy	European	Systems and Resource Management
25	Policy Officer, Environmental Civil Society Organisation	Civil Society Organisation	European	Fertilisers
26	Anonymized	Association	European	Specialty Chemicals
27	Anonymized	Association	National	Resource Recovery from Wastewater
28	Anonymized	EU Institution	European	Circular Economy
29	National Research Centre INIA-CSIC	European Partnership	National	Innovation Partnership
30	Manager	Company	European	Chemical Industry

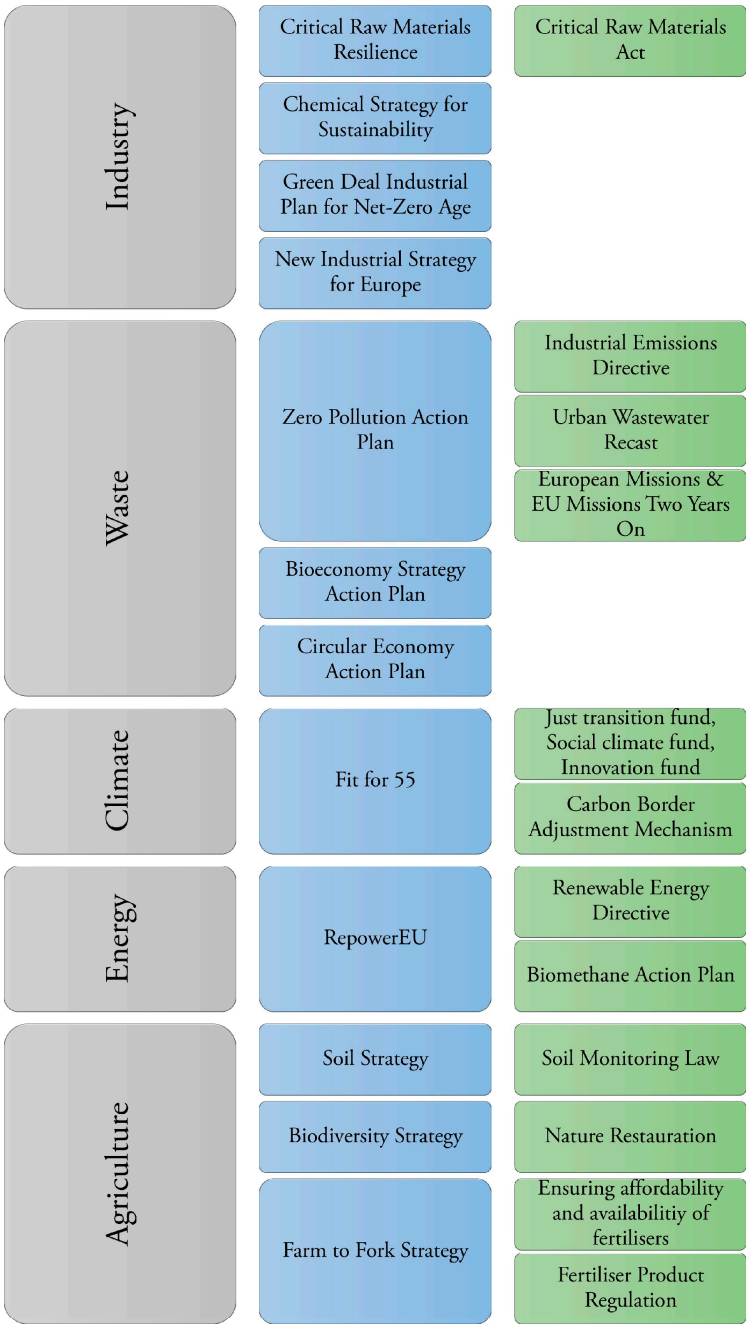


Figure 4. Reviewed sectors (shaded grey), strategies (shaded blue), and laws (shaded green).

4. Results

Description of Meta-Framings

We present the framings derived from the empirical material in Table 2 and describe how they align with the overarching meta-framings (see Annex II for the original dataset). Figure 5 shows the pathways that sponsors have used to progress their framings.

Table 2. The overarching meta-framings comprise accessible general framings, which were developed based on the sponsored, institutional, and spillover framings obtained from the triangulated qualitative data.

Meta-Framing	General Framing	Source			
		Key Sponsors	**Interviews: Sponsored Framing**	**Documents: Institutional Framing**	**Conferences: Spillover Framing**
Fertiliser Self-Sufficiency	Import fertilisers	Farmers, Chemical Industry, Politicians, EU Institutions	Resistance to recovered fertilisers	Import phosphates, subsidise transition to ammonia (Fertiliser Affordability Communication)	Incorporate Recovery Technologies in FPR
	Scale-up recovery technology	Tech Centre, SME, EU Institutions	Standardise risk management to fast-track end-of-waste status	"One Health" approach to risk for people, animals, and environment (Biodiversity strategy, Soil strategy) "One Substance, One Assessment" (Chemical strategy for sustainability) Synergies from cross-sectoral demand (New industrial strategy for Europe)	
	Assign value to recovered fertilisers	Tech Centre, National Association, Consultancy	Assign value to recovered fertiliser to reduce leakage to third countries	Optional end-of-waste harmonisation across member states of the EU (Fertiliser Product Regulation)	Prevent unfair competition through CBAM
Decarbonisation	Farming sufficiency through service provision	Civil Society, Chemical Industry, Tech Centre	Sufficiency approach to farming, remote sensing, and deep learning	Chemicals-as-Service (Chemical strategy for sustainability)	
	Create modules for nutrient recovery from organic waste	Chemical Industry, SME, EU Association, Consultancy, EU Institutions	Wastewater utilities as modular (easy disassemble, repair, and reuse) resource plants of the future	Soils are a recycling machine (Soil strategy) Circularity reduces import dependency (Critical Raw Materials Act)	Warfare-driven destruction of wastewater plants
	Biogas is a rural industry, recovered phosphorus can be used in energy storage	EU Association, Civil Society, Ministry, Corporation	Anaerobic digestion brings biogas industry to rural areas, recovered phosphorus in e-vehicle batteries	Fully substitute Russian fossil fuels with hydrogen and ammonia (RePowerEU, Fertiliser Affordability Communication, Methane Regulation)	Hydrogen limits deployment of renewables
System Change	Design change-oriented regulation	Corporation, Ministry, Phosphorus Platform, Tech Centre, Consultancy	Design change-oriented regulations (tax virgin materials, extend efficiency with wellbeing, finance nature restauration and R&D) connecting high-level objectives with individual goals	Innovate for climate-neutral competitiveness and fairness of the transition (Fitfor55)	Reduce amount and frequency of legislation, focus on implementation
	Use market instruments to select energy-relevant phosphorus recovery solutions	EU Association, Ministry, EU Institution	Devise market pull instruments that support phosphorus recovery frontrunners	Use state aid, critical resource clubs, regulatory sandboxes with energy focus (Industrial Plan for Net Zero Age)	Abandon technological neutrality
	Advance phosphorus recovery as instrument to phase out fossil fuels and mitigate climate change	SME, EU Institution	Add emission factors for recycling to move away from mining and imports of raw materials	Equivalent carbon pricing for imports and domestic products to avoid carbon leakage (Carbon Border Adjustment Mechanism)	Use regulatory sandboxes to phase out fossil fuels

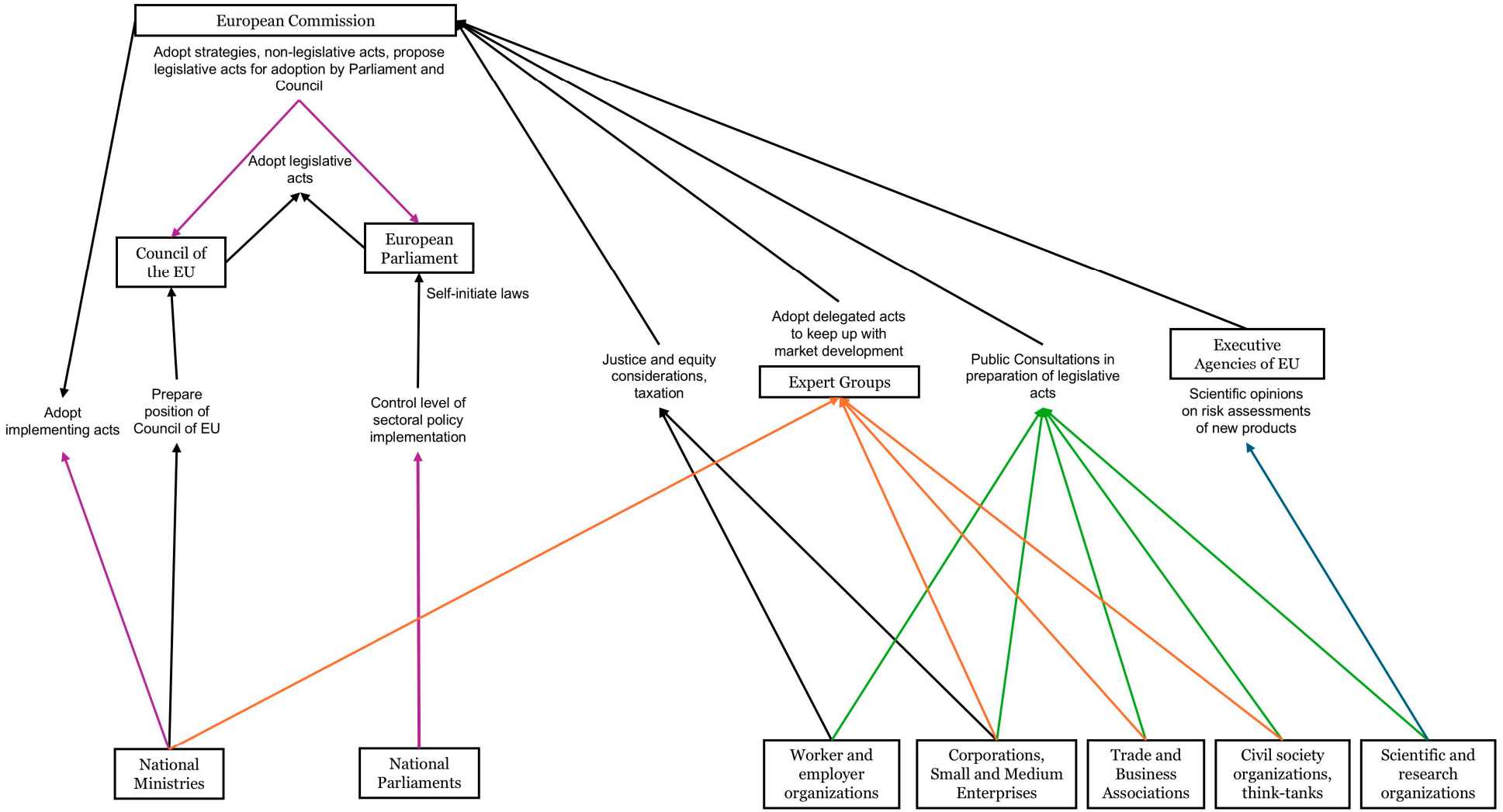


Figure 5. Representation of the pathways for elevation of sponsored framings to the decision-making agenda that was developed through the collected results.

1. **Fertiliser Self-Sufficiency** can be seen as the friction between linear markets dependent on domestic production and imports versus a recovery-focused paradigm. This meta-frame encompassed three general framings:
    - Import fertilisers: This is based on the institutional framing in the EU's communication on ensuring the availability and affordability of fertilisers, which allows gas subsidies and imports of Russian fertiliser as a means to avoid market disruptions. The framing sponsored by farmers and the chemical industry does not endorse recovered fertilisers coming from sludge. The spillover framing is a response by the EU commission that focuses on expanding the scope of recovery technologies included in the Fertiliser Product Regulation;
    - Scale-up recovery technology: This is based on several institutional framings proposing the standardisation of risk assessment carried out before the approval of new products across EU agencies. These are relevant as recovered phosphorus comes from a range of inputs and may be synthesised into a range of products though chemical processes. The sponsored framing aligns with this proposal as it criticises the burdensome testing and approvals of end-of-waste status pursuant to Fertiliser Product Regulation (FPR). Although no spillover framing was identified at the conferences, the EU Industrial Strategy potentially includes it in the framing economies of scale created by synergistic demand from civic and defence industries. This was omitted as it is outside the methodology's scope;
    - Assign value to recovered fertilisers: This is premised on the institutional framing for optional EU-wide harmonisation of end-of-waste status of substances pursuant to FPR, and the sponsored framing that in the absence of such harmonisation, recovered fertilisers are designated for export to third countries outside the EU and should instead be ascribed value. The spillover framing suggests that an option lies in seeing recovered fertilisers as a means to substitute the (Russian) carbon-intensive fertilisers, which are allowed in EU as a means to avoid market disruptions.
2. **Decarbonisation** can be seen as the contribution phosphorus circularity can make to achieving net-zero emissions and was composed of three general framings:
    - Farming sufficiency through service provision: This is built on the alignment between the institutional framing of providing chemicals (and resources) as services and the sponsored framings demanding moving to a sufficiency approach in farming (via less livestock) and usage of remote sensing and deep learning for precision fertilisation and monitoring eutrophication. There was no spillover framing in support of this general framing;
    - Create modules for nutrient recovery from organic waste: This is built on the institutional framing of soils as a recycling machine promoting regenerative circularity and the idea that circularity reduces import dependency, enhanced by the sponsored framing that criticised the restrictive legal status of utilities and proposed their reframing as resource plants built with modules allowing easy disassembly, repair, and reuse. The destruction of wastewater plants as critical infrastructure in Ukraine (Avdiivka) was selected as relevant spillover framing, as it was used by policymakers to attract attention to phosphorus-driven eutrophication and greenhouse gas emissions;
    - Biogas is a rural industry, recovered phosphorus can be used in energy storage: This is built as an alternative to the institutional framing of prioritising hydrogen and ammonia as substitutes for fossil fuels and fertilisers. The sponsored framing suggests instead that public investment should be channelled towards rural anaerobic digestion for biogas and the simultaneous synthesis of recovered

phosphate from dewatered sludge or remaining digestate in the case of manure. This sponsored framing was defended through the idea that it supports farmer livelihoods because remaining digestate can be used to regenerate soils, and that recovered phosphorus (as vivianite) can be used as a cathode in LFP batteries. The spillover framing suggests that the hype around hydrogen restricts investments in renewable energy, and that it should be limited to hard-to-abate industries (e.g., steel and marine transport).

3. **System change** can be explained as the necessity to design instruments that are defined by established sectoral siloes and that translate system-wide objectives to individual responsibilities. It comprises three general framings:
    - Design change-oriented regulation: This is built through the institutional framing that innovation should focus on climate neutrality as a means to achieve competitiveness and redistributing revenues to ensure fairness of the transition for those excessively reliant on fossils, but not having the means to phase them out, and the sponsored framing that suggests several implementing directions (tax virgin materials, extend efficiency with wellbeing, and finance nature restauration and R&D), as well as to define individual goals. The spillover framing suggests that the current amount and frequency of legislation is resulting in regulatory fatigue and that future legislation needs to focus on implementation;
    - Use market instruments to select energy-relevant phosphorus recovery solutions: This is based on the institutional framing that renewable energy and energy storage technologies should be supported with regulatory experimentation in the form of sandboxes, less restrictions on using state aid, and advancing critical resource clubs to achieve net-zero. The sponsored phosphorus framing suggests that even if high recovery rates are achieved, there must be market instruments that can pull recovered phosphorus into the market (e.g., blending obligations). The spillover framing suggests that technology neutrality should be abandoned and instead the EU should bet on pathways that are competitive in a net-zero scenario;
    - Advance phosphorus recovery as an instrument to phase out fossil fuels and mitigate climate change: This is based on the institutional framing that carbon taxation is one of the instruments ensuring a fair level playing field between domestic producers aiming to decarbonise and external counterparts that may engage in unfair practices. It was complemented by the sponsored framing criticising the lack of internationally accredited emission factors for phosphate recovery. The spillover framing suggests that regulatory experimentation should focus on technologies enlisted in the net-zero industry act (biogas, battery storage, and hydrogen) that can phase out fossil fuels.

5. Discussion

This section discusses the framings through Kingdon's three streams concept to identify constraints to and opportunities for the advancement of alternative phosphorus recovery framings.

The Fertiliser Affordability and Accessibility Window

From the institutional framings, we learn that the EU's Green Deal is a legislative programme and a public investment framework with the objective of decarbonising the EU's economy through support for technological advances that require fewer resources, reduce greenhouse gases, and promote renewable energy technologies and resource circularity. Besides supporting green growth, the strategy acknowledges the importance of digitalization and makes fiscal transfers towards those that are most affected and have

fewer resources for adaptation (such as energy-poor households, coal regions, and less developed member states). When it comes to phosphorus recovery, two relevant factors have undermined its role in such a transformation.

Firstly, within its common agricultural policy (CAP) the EU is mandated (see Figure 1) to pursue yield productivity, market stability, and wellbeing-oriented living standards. The external shock of the war in Ukraine increased the prices of fertilisers and, by extension, food production. Hence, to pursue its mandate within the agricultural sector, the EU has tapped into the "Import Fertilisers" general framing, associated with the removal of tariffs and the expansion of the scope of the Fertiliser Product Regulation in line with emerging feedstocks and recovery technologies. However, this has strengthened the position of the domestic agrochemical industry, which also required further support for its decarbonisation. Thus, there are two other emerging general framings related to emergent recovery technologies that build on standardising risks assessments and overcoming the arbitrary application of end-of-waste status across member states. However, the fertiliser self-sufficiency paradigm is dominated by competition between domestic chemical industries and imported fertilisers supplied by carbon-intensive third countries. This is especially evident in the UN-brokered Black Sea Grain deal, which promotes Russian fertilisers and raw materials for ammonia production in exchange for unobstructed shipping of Ukrainian grains [103]. The EU also reduced customs tariffs on fertiliser inputs to improve the affordability of domestically synthesised nitrogen [104].

Secondly, the war on Ukraine triggered a substantial shift towards investment in renewable energy and storage to increase the energy system's resilience. The priority has been replicated in RepowerEU, the EU Methane Regulation, the Green Deal Industrial Plan for the Net-Zero Age, as well as, notably, the Fertiliser Communication. Hydrogen has been set out as a political priority due to its possible synthesis via water electrolysis, while other energy recovery pathways (framed in policy circles as "clean molecules") have been included in the technology neutral pathway advanced by the EU fertiliser industry [105,106]. They include the anaerobic digestion of biogas containing 50–75% methane, 25–50% carbon dioxide, and traces of nitrogen and hydrogen sulphide [107]. The biogas/biomethane can be split into hydrogen through (steam) methane reforming, and carbon dioxide and the process can be reversed via the methanation of carbon dioxide captured from industrial installations and hydrogen [108]. While these opportunities can act as drivers for nutrient recovery that precedes the anaerobic digestion of biomass, they have not received significant political attention.

These factors contextualised the limited inclusion of the fertiliser self-sufficiency and decarbonization meta-framings in the problem definition and the policy responses outlined in the communication. More precisely, the "Import Fertilisers" general framing is used to present food security in relation to domestic industry's dependence on natural gas:

- *"In summer 2022, gas accounted for up to 90% of the variable production cost of the ammonia production in the EU";*
- *"The global scarcity of fertilisers is primarily caused by the high price of natural gas which is necessary for the production of nitrogen fertilisers".*

This cost rationale has been used to defend several policy responses that can improve conditions for EU industry and ensure a stable fertiliser supply (improved access to natural gas, improved market transparency through a fertiliser market observatory, supporting the nitrogen industry's transition to ammonia, supporting hydrogen, and trade diversification).

Secondly, the Fertiliser Communication mentions the strategic objective of a 50% reduction in losses and the structural solution of accelerating the transition to sustainable food production and innovative technologies without jeopardising affordability. There are, however, several issues with these policy responses. Noticeably, the communication proposes *improved access to organic and recovered fertilisers*, which corresponds to the general framing of "scale-up recovery technology"; however, without mentioning the difficulties related to achieving end-of-waste status. There is also a noticeable emphasis on the target of achieving 25% organic fertilisers as a way to reduce emissions and substitute mineral fertilisers. However, as the formulations do not mention recovered fertilisers in this transition, they fail to make use ofthe general framing "assign value to recovered fertilisers".

In the absence of the mentioned integrated nutrient management plan (INMP), which was meant to implement the strategic objectives of loss reduction, crop diversification management practices reducing nutrient use (precision agriculture machinery, agro-ecological methods such as diversification, rotation with plant proteins, usage of catch crops, and organic farming), as well as the rollout of the Farm Sustainability Tool For Nutrients (EU's remote sensing platform), these objectives are suggested as possibilities that can be financed through the national CAP strategic plans. However, since CAP is a shared competence (Figure 1), all of them remain voluntary. This undermines their consolidation under the general framing "farming sufficiency through service provision". Applying sufficiency as an ethno-social concept of wellbeing to the biophysical realm of agriculture requires removing the CO_2-intensive excesses that do not contribute to human need [109] and that can slash 72% of phosphorus demand if meat is phased out [3]. However, such actions are contentious, as 46.5% of direct payments, which constitute 72% of the total CAP funding, are oriented towards (non-dairy) grazing livestock [110,111]. Research suggests that economic policies may be the answer to reduce phosphate loading from livestock; however, this has only been tested with a cap-and-trade phosphate rights system in the Netherlands, which had limited results [22,112,113]. Another possibility to reduce phosphorus loading and increase productivity lies in decreasing livestock density and rotating land uses within integrated crop–livestock systems [114,115]. However, the EU's fertiliser industry, represented in the study, suggested rather that the efficiency rationale of the Zero Pollution and Farm to Fork strategies (50% less losses and 20% less chemical fertiliser) can be implemented via precision application aided by remote sensing. Effectively, even if consolidated, the "farming sufficiency through service provision" general framing would still lack a redistributive focus towards carbon emission-offsetting practices.

Lastly, actions for achieving resilience are mostly designated for the purchase (855 million euro) and storage (450 million euro) of chemical fertilisers. Despite the available funding of 9 billion euros in Horizon Europe, only 185 million are mobilised for fertiliser research. Resilience can also be achieved via the scaling-up of emergent circularity solutions contributing to decarbonization, outlined in the "create modules for nutrient recovery from organic waste" and "biogas is a rural industry, recovered phosphorus can be used in energy storage" general framings. Although stakeholders support EU-wide obligations for phosphorus recovery from wastewater that can drive the scaling-up of nanotechnology-based adsorption modules, German and Austrian national laws [116,117] prefer incineration, as health hazards reduce options and limit the possibility for a harmonised EU-wide approach towards recovery. However, prioritising certain pathways in respect of subsidiarity can streamline funding and consolidate efforts.

Secondly, biomethane gas has been mentioned as an income possibility for rural areas, but not as a driver for recovery. Instead, it is presented only as a driver for organic agriculture, which is emphasised as a CO_2-reduction possibility. This limits the researchers and farmers' attention only to recovery technologies allowed as organic fertilisers, such as struvite, instead of exploring others with lower technological readiness, but with relevance for energy systems' resilience, such as vivianite.

> *"Using vivianite as fertiliser could be a serious contender in some niche markets. Even more compelling is the fact that vivianite could be a perfect raw material for Lithium-Iron-Phosphate batteries, which do not require cobalt."* [118]

This is a missed opportunity, as vivianite recovery from manure could be included in National CAP Strategic Plans, and as much more funding is made available for compensations and investments in renewable energy sources, such as biogas through the temporary crisis framework and the cohesion funds (180 billion euro). Lastly, the communication sets out a long-term target of green hydrogen's competitiveness, expected to be reached vis à vis potentially rising natural gas prices. These uncertain long-term projects undermine the already existing potential of wastewater treatment to provide renewable nutrients and biogases and contribute to human wellbeing by reducing health hazards and greenhouse gas emissions.

Notably, these projects reflect the official positions of the EU nitrogen fertiliser industry, which sets out two ammonia decarbonisation pathways: one based on electrolysis for green hydrogen and the capture of CO_2 from air, and a more technology-neutral pathway inclusive of biogases and carbon capture and storage [105,106]. While the substitution of natural gas with recovered biogas in the steam methane reforming process of hydrogen production is the most cost-effective solution in the report, this is presented through coupling with organic fertilisers, and not emphasised as driver for their recovery in general. Instead, the EU nitrogen industry has explicitly tapped into ammonia as a decarbonised replacement of natural gas in power generation and marine shipping. Effectively, this has neutralised biogas as a political priority, and instead allowed ammonia to be emphasised in the EU's communication as a diversification pathway for Russian gas imports.

Thus, phosphorus stakeholders' propositions within the decarbonisation meta-framing have been sidetracked from the communication's foci on energy system resilience and fertiliser decarbonisation. Seen from Kingdon's conceptual interpretation, the Ukraine crisis has acted as a trigger for the moving of the fertiliser issue towards a globally recognisable **problem**. However, the EU's policy response has paid asymmetric attention to the feedback of its own nitrogen fertiliser industry, which has adeptly interpreted the coupled natural gas and fertiliser commodity price shocks. This affordability paradigm applied internally is also not reciprocated in its external cooperation, where the EU's communication supports agro-ecological methods and uses its development cooperation portfolio of instruments (DeSIRA: Development of Smart Innovation through Research in Agriculture, GCCA+: Global Climate Change Alliance+) to support the scaling-up of farmers' climate-relevant agro-ecological innovations, either by connecting them with research and private sector agri-value chains or with carbon markets. These efforts echo COP27's Agricultural Innovation Mission for Climate that supports the inclusion of climate-smart agriculture in the nationally determined contributions to climate change mitigation [119]. Importantly, nutrient recycling is one of the principles of agro-ecology [120], yet the EU's internal target of 25% organic agriculture has superseded most recovery-focused formulations in the Fertiliser Communication. As a result, similarly to the nitrogen industry's decarbonisation programme, recovered fertilisers have not been assigned CO_2 and gas dependence reduction properties.

The Green Deal Industrial Plan for the Net-Zero Age, the Fit-for-55 climate strategy, and the CBAM regulation provide several system change propositions that could address the aspects undelivered by the EU's Fertiliser Communication. A key aspect raised by high-level consultancies hosting previous EU commissioners and national ministries is the necessity to design change-related regulations that ensure the delivery of the EU's climate objectives through impactful measures that make use of advances in sustainability. In the same way that steel can be substituted with wood to achieve a change in system design, so can recovered fertilisers. Most of these actions would certainly rely on active spending to shift the growth towards emergent solutions. However, the key problem to achieving these objectives is that these ideas (see Table 2) are not supported by knowledge communities with sufficient access to EU institutions as gatekeepers, or are lacking non-technical boundary spanners that can translate technical expertise in a way that speaks to the EU's high-level priorities. EU institutions' representatives have been markedly in favour of using market instruments such as high taxes on landfilling and pollution; however, the ESPP has mostly devised regulatory propositions for pull actions [121]. At the same time, bottom-up innovations such as regulatory sandboxes with an energy focus and permissible supply-side actions such as state aid for scaling-up strategic projects have not been borrowed by phosphorus communities, as these lie outside of their usual sectoral scope. Lastly, SMEs that have become interested in implementing phosphorus recovery besides their nitrogen recovery activities have suggested that the EU has not paid sufficient attention to developing emission factors for recovery from different streams (e.g., fish waste in aquaponics) that can be used to defend supply-side actions.

From Kingdon's prism, we can therefore say that in the **policy** stream, the EU has recognised the EU nitrogen industry's ammonia decarbonisation pathways, while cautiously postponing emergent alternatives. Its gatekeeping has focused on energy policy rationales in line with the necessitated decoupling from Russia. The fact that ammonia is currently produced via grey hydrogen steam methane reforming and that green hydrogen constitutes only 0.13% of the supply [122,123] is expected to be reversed by gas market pricing in the future. In the meantime, carbon capture and the storage of nitrogen plants will remain the preferred retrofitting strategy [124], despite ammonia being hazardous, requiring energy for conversions and more land and water than other pathways [39,125]. When it comes to ascribing value to recovery, the EU has also made the choice to do so only for organic fertilisers. Notably, these decisions have been made to the detriment of the emergent alternatives described in the decarbonisation meta-framing.

The **politics** of these decisions can be positioned in the socio-institutional space through the "regulatory" fatigue from the EU's legislative programme that has affected multiple stakeholders. Most notably, these are the farmers, whose protests watered down science-backed policy targets for nature restauration through 10% non-commercial land use, the abolishment of chemical pesticide (glyphosate) reduction targets that were the same as those for fertilisers, and removing nutrient plans and eco-schemes' conditionality from CAP [126,127]. Nitrogen has also received higher attention than eutrophication from phosphorus during these protests, due to the specifics of Dutch loading with nitrogen. Lastly, farmers' discontent with rising prices has reinforced chemical industries' case for subsidies as a tool to address the commodity price shocks, in neglect of warnings that profits that are already centralised by the chemical industry and additional supply of chemical fertiliser will slow the shift to alternatives [128,129]. We depict the three streams and policy choices made in the EU's Fertiliser Communication in Figure 6.

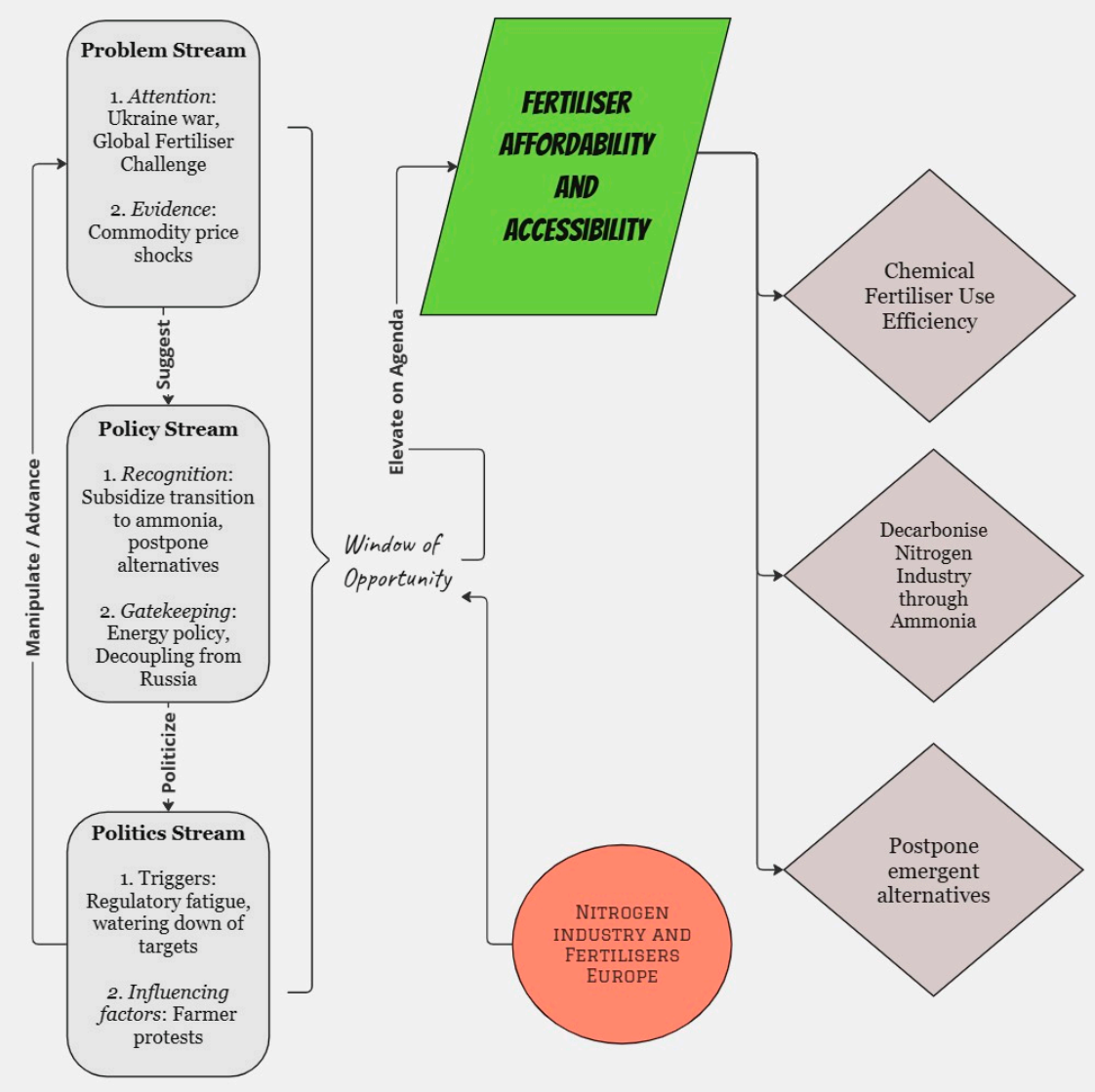


Figure 6. The fertiliser affordability window depicting the current situation.

The window of opportunity opened by the EU elections (2024–2029)

The Fertiliser Communication was adopted as a soft law instrument meant to steer actors in multi-level systems through allocating responsibilities and monitoring prescriptive non-binding targets that promote actors' learning alongside the "open method of coordination" [130]. Soft law initiatives, formally labelled Team Europe, function as a mobilising factor when a clear political objective and targets are provided, and such is necessary for nutrient recovery. However, in contrast to critical raw materials (CRM), the EU has yet to adopt an act specific to nutrients. This has been acknowledged by the strategic dialogue on agriculture completed in 2024, which sets out autonomy, the usage of human waste, and closing phosphates cycles as priorities for INMP [131]. The forthcoming updates of the CAP, the expected Circular Economy Act, and the EU's CBAM implementing the overarching priorities of quality of life and competitiveness outlined in the Commissions' work programme for 2024–2029, are further possibilities for embedding nutrient recovery in the existing governance [132]. The updated climate aspirations (90% emission reduction by 2040) also support the creation of a single market for circular raw materials such as phosphorus, decarbonising agriculture strategy through mitigation technologies and focusing on supply-side investments in climate solutions [133,134]. The new European Commission and parliament and the advent of a new Green Deal Industrial Plan have

shifted the priorities on the decision-making agenda. Nevertheless, the right combination of salient spillover framings may still open windows of opportunity for the elevation of hitherto postponed alternative intersectoral framings.

In the **problem stream**, we can expect that framings tapping into the resilience, autonomy, and competitiveness of the EU's economy will be attracting policymakers' attention. Considering that LFP technologies may be on the rise, the problem definition must analyse supply chain inefficiencies also through the growing intersectoral demand for phosphorus, so that policy responses address the market dynamics that may otherwise hinder food security. The 2024–2029 cycle dynamics outlined above present a possibility to rethink phosphorus circularity as a climate mitigation strategy applied not only to organic fertilisers (which are subject to stricter regulatory approvals), but also to technical and advanced chemical recovery of nutrients from organic wastes such as manure and wastewater. Such a paradigm could position recovery against the linear production of fertilisers that is dependent on fossil fuels. One key target that can mobilise stakeholders can be found in the CRM Regulation, which recommends 25% recycling targets for strategic materials with non-agricultural use [135]. It must be emphasised that the currently reported rate of 17% phosphorus circularity in the EU's documents relates only to the direct application of manure and sludge in agriculture and stifles the momentum for the advanced technical and chemical recycling of organic wastes [18]. As the completion of the single market for recovered resources is increasingly seen through the prism of industrial policy (see Figure 1), the 12% industrial circularity in the EU compared to the viable 34% achieved by the Netherlands should also be emphasised [136]. Overall, to set out higher recycling targets, stakeholders must position their actions in line with the definition of strategic raw materials that relates to the twin green and digital transformation, and not that of proneness to supply disruptions, which defines resource criticality.

In the **policy stream**, institutional gatekeepers are expected to prioritise the long-term goals of agriculture, energy system resilience, accelerating their decarbonisation through public investment in carbon footprint reduction, and employing trade policy tools to defend new business models [137,138]. However, as seen in the analyses above, the linear production of fertilisers has more authoritative sponsorship and resources, and may centralise these funds. While the food industry prefers primary phosphates, research and development support could focus on scaling-up recovery technologies that substitute technical grade P-acid, as these have higher returns on investment and may bring authoritative sponsors (e-vehicle manufacturers, microchip industry). Since the EU does not have its own primary production of phosphorus, advancing chemical recycling could be incorporated into climate policy, not only as public investment in mitigation but also as corporate carbon offsetting. To avoid the leakage of these recovered resources as exports, measures must be taken towards completing the single market of end-of-waste products. Lastly, the policy of reducing losses by 50% and chemical fertilisers by 20% should include sufficiency measures in agriculture that reduce fertiliser demand by reorienting phosphorus towards plant and dairy protein.

Within the **politics stream,** the national mood towards decarbonisation will continue to play a central role. Therefore, policy responses should find a balance between EU-centred priorities such as competitiveness and providing appropriate incentives to particularly vocal groups such as farmers [139]. The funds outlined in Fitfor55 climate strategy for 55% emission reduction by 2030 defined different levels of granularity for their redistribution, and would dictate more support for rural regions and weaker groups affected by the transition. Since it is expected that geopolitical challenges may persist, circularity may continue to be justified as decoupling from strategic competitors [140]. The emergent intersectoral alternatives (with limitations in Table 2) postponed as a response to the

Ukraine crisis could be elevated on the EU's policy making agenda by selective coupling with the high-level priorities outlined by the Commission and the Council. We present five non-prescriptive combinations that were limited by the scope of our data collection below (see Figure 7).

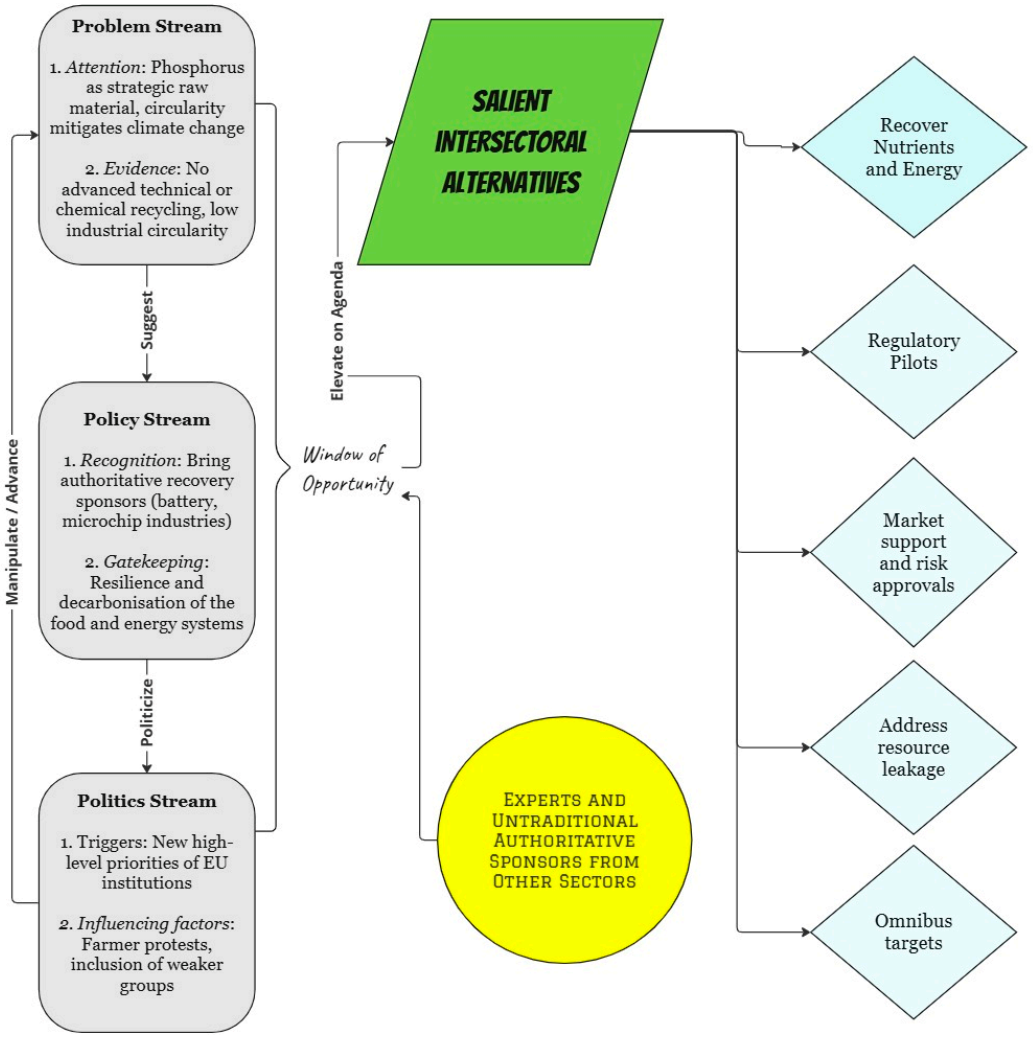


Figure 7. The window after the 2024 European Elections.

Alternative intersectoral framings of phosphorus

We identify five emergent intersectoral framings of phosphorus that trigger policy learning and whose salience could be enhanced though spillover framings:

1. **Recover Nutrients and Energy:** The "Hydrogen limits deployment of renewables" spillover can be used to scale-up phosphorus recovery through vivianite precipitation for potential usage in LFP batteries, while simultaneously digesting organic wastes anaerobically to synthesise biogases containing small amounts of hydrogen [141] and returning the remaining digestate to replenish soil organic matter [118,142]. This holistic sustainability solution could address decoupling from fossil fuels, as it could satisfy 14–32% of the energy share in the EU [143], produce a slow-release fertiliser with 8–16% improved phosphate uptake [144], and replenish soil matter. As such, it can defend phosphorus' understanding as a strategic raw material subject to 25% recovery obligation in the CRM Regulation. Additionally, the "Warfare-driven destruction of wastewater plants" can be used to advance the demonstration of repairable nano-adsorption modules, which can be used both in rural areas to treat

manure and in urban areas to threat wastewater. They would be eligible for financial support from the ETS/CBAM-powered Innovation Fund, as well as from private sector financing in accordance with EU taxonomy for sustainable investment. If cross-border, significant in size, and incorporating priorities from multiple sectoral strategies (e.g., AI optimisation), such projects could be eligible under the Important Project of Common European Interest scheme to create innovative business ecosystems for batteries and hydrogen value chains [145]. Lastly, such modules can be used in the EU's development cooperation;

2. **Regulatory pilots:** The "Use regulatory sandboxes to phase out fossil fuels" spillover can be used to test regulatory pilots in the derogation of existing laws under the net-zero industries act [146], which enlists batteries for storage and biogas synthesis as priorities [147]. These bottom-up solutions are expected to play a central role in technological scaleups under the forthcoming European Innovation Act [148]. Similarly to living labs, they bring added value by collecting evidence on demand reduction, recovered fertiliser acceptance, and upscaling potential [149]. Quantitative evidence on reduced fossil fuel imports and mitigated greenhouse gas emissions could be used to justify impact or venture capital investment in such biowaste industries [150]. At the same time, such pilots are underused in sustainability. While 57 countries have adopted sandboxes in Fintech [151], in the EU, these are mostly limited to renewable energy [152]. Since phosphorus recovery models are constrained by end-of-waste status [153], their application could focus on goal-focused sandbox models that can allow a shift from restrictive ex ante precautionary principles to ones applied before demonstration [154]. As wastewater plants may be legally restricted to produce fertiliser, biogas, or electricity, the testing of new technologies could focus on turning them into energy plants, resource mines, or other legally compatible formulations. Secondly, to enable soil regeneration, digestate or other organic byproducts can be tested regulatorily as amendment solutions, sequestering carbon via enhanced plant growth. Alternatively, if the income of farmers is a priority, regulatory testing could focus on collaborative production and consumption models, where manure is provided to digesters in exchange for fertilisers or energy. In consideration of the "farming sufficiency through service provision", pilots could also focus on redistributing capital from carbon markets by redirecting manure from dairy livestock or biochar towards alternative proteins such as pulses. These models could use blockchain to verify emissions and ensure payments. If successful, such pilots could be used to promote ex post risk approvals of agri-value chain innovations through trade agreements [155];
3. **Market Support and Risk Approvals**: The spillover "Abandon technological neutrality" could be used to scale-up recovery technologies relevant to the energy system. They may require both relaxed state aid rules as well as amending existing regulatory instruments to achieve a market pull effect. Stakeholders in the study have expressed support for EU-wide recovery and blending obligations, but a fuller list is compiled by the ESPP [121]. The valorisation of wastes is further impeded by the lack of regulatory harmonisation of contamination thresholds and stricter risk criteria in some member states, which impede intra-EU trade [156–158]. Currently, struvite is the only technology whose market feasibility is studied by the Joint Research Centre of the EU and that is regulated as an organic fertiliser, but such information is missing for vivianite and biochar [159,160]. These processes are subject to strict veterinary (and phytosanitary if traded in third countries) control, but could benefit from borrowing the institutional approaches to risk harmonisation across sectors outlined in the results. While relevant predominantly for different EU agencies, successful standards could be promoted at

the multilateral level though cooperation with the FAO-WHO Codex Alimentarius. Such measures could lay the foundation of resource recovery clubs;

4. **Address resource leakage:** The "Prevent Unfair Competition through CBAM" spillover can be used to address not only the leakage of carbon to third countries, but also the leakage of recovered phosphorus happening because of the optional harmonisation of end-of-waste status across the EU's member states. The current scope of CBAM includes phosphate rock and mixed fertilisers, and would tax the carbon content of otherwise freely imported primary fertilisers. Among the most affected by this action would be Russia, which is also the biggest exporter of phosphates into the EU [43,161]. Currently, CBAM revenues go into the EU's Innovation Fund, but could be used both to reinvest in recovery infrastructure and the carbon accounting of output products coming from it to justify further investments. Emissions accounting for recovered resources as a connection with CBAM can be promoted at the G7 Alliance and G20 Dialogue on resource efficiency to build integrated climate and circular economy clubs and diffuse the practice in upstream markets. The impact of these measures could be high, as while CBAM may trigger the adoption of emission trading in 36–58 countries [162], connecting the instrument with recovery may communicate its priority to 110 countries that have adopted circular economy measures [163];
5. **Omnibus targets:** The "Reduce amount and frequency of legislation, focus on implementation" spillover can be used to design change-oriented regulations that cumulate unrelated targets by connecting them with overlapping high-level objectives related to climate neutrality, resilience, competitiveness, wellbeing, and restauration. Examples related to phosphorus recovery include mitigated emissions, recovery obligations, connections with energy neutrality, net income gains, and restored soil biomass. While the current FPR suggests a CE mark only for fertilisers approved across member states, the EU has a much more potent labelling competence within the CAP. It could allow the embedding of similar targets under an omnibus "true cost of food" labelling that would improve the visibility of socio-environmental considerations and act as a behavioural nudge for individual responsibility. It is expected that consumer choices related to recovered fertilisers may lead to a 4–7% reduction in climate change and could be verified through funding targeting EU Missions [164].

It must be noted that these combinations are subject to the limitations of the collected interviews and observations, respectively, sponsored and spillover framings. We attempt to improve the study's relevance by outlining other emergent recovery pathways in the section below. Nevertheless, the identified institutional framings can be used to replicate the study. Their framings reveal a multitude of high-level objectives adopted during the EU Green Deal, which have been updated with those hitherto established for the 2024–2029 working programme of the EU. We can expect that in the long-term, the affordability rationale will be complemented by or substituted with one related to climate mitigation. Health and wellbeing concerns would also be important in defending the costs of non-action. During the study, we also learned that the resilience of agricultural and energy systems will remain highly relevant. Stakeholders and environmental activists interested in phosphorus could use these rationales to defend their scaling-up efforts, and widely speaking, resource recovery. We believe that a major window of opportunity has opened with the inauguration of a new European Commission. The five measures outlined above could also contribute to strategic environmental goals such as reducing fossil fuel usage and replicating nutrient recovery as a priority in third countries through CBAM [127,138].

Other considerations

Wastewater is expected to grow by 50% by 2050. It contains five times more energy than what is required to treat it, yet more than 80% of it is untreated [165]. Full nutri-

ent recovery can satisfy 6.8% of the global phosphorus demand, 14.4% of nitrogen, and 18.6% of potassium, bring 13.6 billion USD investment returns, and power 239 million households [166]. Besides their nutrient and energy recovery potential, investments in wastewater contribute to carbon neutrality by limiting carbon dioxide, nitrous oxide, and methane emissions, and their monitoring is key to select mitigation strategies in comparable contexts [167–169]. Such measurements can also be used to unlock climate mitigation funding from carbon taxes, credits, or sustainable investments. These, in turn, should focus on a transition towards nutrient recovery and data generation through monitoring of the process.

In principle, there are biological, chemical, and bioelectrochemical processes for nutrient concentration in sludge [170]; however, most plants focus on phosphorus removal and discharge limits instead of its recovery [171–173]. Advancing recovery is also important, as despite the illegality of discharge in the EU, sewage overflow, clogging and breakage, and salinity-induced corrosion due to rainfall variations may still lead to eutrophication [174–176].

Among the more advanced recovery techniques is struvite precipitation, which may contain ammonium salts, but is less bioavailable and captures only up to 40% of phosphorus [170,177,178]. Due to the obtained results, we focused on the magnetic recovery of vivianite as a highly suitable pathway for several member states, which can achieve up to 70% phosphorus recovery, but is currently in its demonstration phase [179,180]. Another pathway worth investigating is the pyrolysis or hydrothermal carbonisation of dewatered sewage sludge to produce biochar, which has decontamination and nutrient retention properties, can sequester carbon, and act as an amendment in soils, but may be less suitable as a fertiliser [181]. These recovery pathways should be considered based on local economic conditions and the economic implications of selecting either anaerobic digestion for biogas or dewatered sludge pyrolysis to produce biochar [182,183]. Lastly, high amounts of phosphorus can be recovered after sludge incineration, but this technique bears low bioavailability and low energy recovery [184–186].

6. Conclusions

This article expands the sectoral scope of analysis to overcome the siloed understanding of phosphorus governance, and makes several contributions to the literature.

Firstly, it fills a methodological gap by applying the three streams conceptual framework for agenda-setting and employing framing as an analytical heuristic in phosphorus research. Secondly, it critically analyses the shift to non-binding soft governance tools cumulated in the EU's communication on the accessibility and affordability of fertilisers to inform stakeholders of the EU's actions. The document was adopted in response to the commodity price shocks exacerbated by the Ukraine crisis and the identification of the global challenge of fertiliser affordability. The EU's response consisted of providing gas subsidies to stabilise fertiliser prices and replicating the preferred decarbonisation pathways of the nitrogen agrochemical industry, without emphasising the potential of emergent phosphorus recovery technologies that can be combined with the anaerobic digestion of biogases. This centralised revenues in linear production and postponed the transition to a circular economy of organic wastes that can strengthen the food system's resilience and contribute to the resilience of the energy system.

Thirdly, the article outlines the inauguration of the new European Commission as a policy window for elevating the emergent phosphorus governance framings that can create a more coherent, intersectoral, and transformative governance.

Lastly, we propose five bottom-up alternatives developed through stakeholder-sponsored framings and salient spillover framings that can trigger this transformation though policy learning, better integration with related sectoral strategies, and laws promul-

gated as part of the EU Green Deal. They focus on recovering fertilisers and energy-relevant outputs, which can improve the understanding of phosphorus as a strategic raw material and thus increase the obligatory rates of recovery it is subject to. To strengthen the case for scaling-up, we also suggest using sandboxes as bottom-up regulatory pilots, supply-side investment and market pull support tools, harmonised risk approaches, addressing the leakage of recovered resources in third countries, as well as using omnibus targets to assign individual responsibilities. We believe that these can serve to inform stakeholder efforts and replicate recovery as a priority in third countries. To improve the relevance of the study, we also suggest other recovery pathways that are worth exploring, such as biochar.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su17041478/s1.

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Appendix A

Annex I. Interview Guide

SYSTEM FRAGMENTATION

1. How would you describe the current phosphorus system?

1.1. Do you recognize any problems/challenges in your (partners') work related to phosphorus recovery? What is their nature, what do they stem from? (or) Have you been subjected to duplicating or conflicting stimuli, objectives, regulations, requirements, certifications, etc. related to phosphorus recovery and innovation?

1.2. Do you believe (the current) regulatory frameworks (e.g., EU fertilizer Regulation, CE Action Plan) are helpful for increasing recovery and innovation? (or) Has the lack of regulation or stimuli targeting innovation helped you in particular instances?

2. Who would you "call" if you wish to propose changes in the way phosphorus recovery is done?

2.1. Would it be a business association, non-governmental organization, body of your government or an EU institution?-

2.2. Do you feel sufficiently empowered to change the decision-making agenda? Do such events help you channel demands for policy improvements to decision-makers?

3. Could you enlist any organizations that support you in your work with Phosphorus recovery?

3.1. Which of your collaborators have central importance in brokering innovative technology to decision-makers or challenging existing rules?

3.2. Are these exchanges contractual or rather more informal? Do any of them resort to connections in other influential networks of actors to maximize these efforts?

CIRCULAR PHOSPHORUS ECONOMY

4. Have any of them helped you achieve a (more radical) vision of circular economy in your work?

4.1. What innovative phosphorus futures would look like within a circular economy? Which Phosphorus recovery activity should be prioritized?

4.2. How could policy act as enabler of innovative circular business models which are based on phosphorus recovery?

5. Do you think phosphorus circularity could lead to new business models (beyond fertilizers)?

5.1. Do you believe added circular value within these can help accelerate phosphorus recovery?

5.2. What can improve the demand for recovered Phosphorus?

INSTITUTIONAL INNOVATIONS

6. Have you noticed any institutional innovations that have overcome hindrances to phosphorus recovery and upscaling to novel products?

6.1. How did they come into being? Have technological and infrastructural capacity, particular European strategies or major events outside the EU been their driver?

6.2. What could potentially bring such them into being?

7. Would you like to see a fast-track authorization for phosphorus recovery for novel circular products?

7.1. Would you rather see economic stimuli for phosphorus recovery or improved technology and infrastructure?

7.2. Would you rather prefer a guidance document that prioritizes recovery models in a taxonomy?

8. If you had a chance to propose a policy (including, but not limited to legislative change) that maximizes the best practices of your work what it would be and to whom you would like to propose it?

References

1. Will, J.B.; Mark, A.S.; Kate, V.H.; Dave, S.R.; Bryan, S. (Eds.) 2022 Our Phosphorus Future: Towards Global Phosphorus Sustainability. Edinburgh, UK Centre for Ecology & Hydrology, 371pp. (INMS Report no. 2022/01). Available online: https://nora.nerc.ac.uk/id/eprint/533099/ (accessed on 2 January 2025).
2. Lun, F.; Sardans, J.; Sun, D.; Xiao, X.; Liu, M.; Li, Z.; Wang, C.; Hu, Q.; Tang, J.; Ciais, P.; et al. Influences of international agricultural trade on the global phosphorus cycle and its associated issues. *Glob. Environ. Change* **2021**, *69*, 102282. [CrossRef]
3. Metson, G.S.; Bennett, E.M.; Elser, J.J. The role of diet in phosphorus demand. *Environ. Res. Lett.* **2012**, *7*, 044043. [CrossRef]
4. McDowell, R.W.; Pletnyakov, P.; Haygarth, P.M. Phosphorus applications adjusted to optimal crop yields can help sustain global phosphorus reserves. *Nat. Food* **2024**, *5*, 332–339. [CrossRef] [PubMed]
5. Chen, M.; Graedel, T.E. A half-century of global phosphorus flows, stocks, production, consumption, recycling, and environmental impacts. *Glob. Environ. Change* **2016**, *36*, 139–152. [CrossRef]
6. Jama-Rodzeńska, A.; Białowiec, A.; Koziel, J.A.; Sowiński, J. Waste to phosphorus: A transdisciplinary solution to P recovery from wastewater based on the TRIZ approach. *J. Environ. Manag.* **2021**, *287*, 112235. [CrossRef]
7. Cordell, D.; White, S. Life's bottleneck: Sustaining the world's phosphorus for a food secure future. *Annu. Rev. Environ. Resour.* **2014**, *39*, 161–188. [CrossRef]
8. Bobba, S.; Carrara, S.; Huisman, J.; Mathieux, F.; Pavel, C. Critical Raw Materials for Strategic Technologies and Sectors in the EU—A Foresight Study; 2020. Available online: https://rmis.jrc.ec.europa.eu/uploads/CRMs_for_Strategic_Technologies_and_Sectors_in_the_EU_2020.pdf (accessed on 2 January 2025).
9. Spears, B.M.; Brownlie, W.J.; Cordell, D.; Hermann, L.; Mogollón, J.M. Concerns about global phosphorus demand for lithium-iron-phosphate batteries in the light electric vehicle sector. *Commun. Mater.* **2022**, *3*, 14. [CrossRef]
10. Lunde, A.E. Investigating How the LFP Battery Demand Is Shaping the Future of Phosphorus and the Role of Secondary Resources. Available online: https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/3023802?show=full (accessed on 2 January 2025).
11. Bai, Z.; Liu, L.; Obersteiner, M.; Mosnier, A.; Chen, X.; Yuan, Z.; Ma, L. Agricultural trade impacts global phosphorus use and partial productivity. *Nat. Food* **2023**, *4*, 762–773. [CrossRef] [PubMed]
12. Brownlie, W.J.; Sutton, M.A.; Cordell, D.; Reay, D.S.; Heal, K.V.; Withers, P.J.A.; Vanderbeck, I.; Spears, B.M. Phosphorus price spikes: A wake-up call for phosphorus resilience. *Front. Sustain. Food Syst.* **2023**, *7*, 1088776. [CrossRef]
13. Daramola, D.A.; Hatzell, M.C. Energy Demand of Nitrogen and Phosphorus Based Fertilizers and Approaches to Circularity. *ACS Energy Lett.* **2023**, *8*, 1493–1501. [CrossRef]
14. Kalpakchiev, T.; Fraundorfer, M.; Jacobs, B.; Martin-Ortega, J.; Cordell, D. Transforming the European Union's phosphorus governance through holistic and intersectoral framings. *Front. Sustain. Resour. Manag.* **2023**, *2*, 1273271. [CrossRef]
15. Canziani, R.; Boniardi, G.; Turolla, A. Phosphorus recovery—Recent developments and case studies. In *Sustainable and Circular Management of Resources and Waste Towards a Green Deal*; Elsevier: Amsterdam, The Netherlands, 2023; pp. 269–281. [CrossRef]
16. Teah, H.Y.; Onuki, M. Support phosphorus recycling policy with social life cycle assessment: A case of Japan. *Sustainability* **2017**, *9*, 1223. [CrossRef]
17. El Wali, M.; Golroudbary, S.R.; Kraslawski, A. Impact of recycling improvement on the life cycle of phosphorus. *Chin. J. Chem. Eng.* **2019**, *27*, 1219–1229. [CrossRef]

18. European Commission. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability. 2020. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52020DC0474 (accessed on 2 January 2025).
19. Rosemarin, A.; Ekane, N. The governance gap surrounding phosphorus. *Nutr. Cycl. Agroecosystems* **2016**, *104*, 265–279. [CrossRef]
20. Ashley, K.; Cordell, D.; Mavinic, D. A brief history of phosphorus: From the philosopher's stone to nutrient recovery and reuse. *Chemosphere* **2011**, *84*, 737–746. [CrossRef] [PubMed]
21. Dixon, M.W. Chemical fertilizer in transformations in world agriculture and the state system, 1870 to interwar period. *J. Agrar. Change* **2018**, *18*, 768–786. [CrossRef]
22. Garske, B.; Ekardt, F. Economic policy instruments for sustainable phosphorus management: Taking into account climate and biodiversity targets. *Environ Sci Eur.* **2021**, *33*, 56. [CrossRef]
23. Sandström, V.; Kaseva, J.; Porkka, M.; Kuisma, M.; Sakieh, Y.; Kahiluoto, H. Disparate history of transgressing planetary boundaries for nutrients. *Glob. Environ. Change* **2023**, *78*, 102628. [CrossRef]
24. UNEP. What Is Phosphorus and Why Are Concerns Mounting about Its Environmental Impact? Available online: https://www.unep.org/news-and-stories/story/what-phosphorus-and-why-are-concerns-mounting-about-its-environmental-impact#:~:text=%E2%80%9CReducing%20nutrient%20pollution%20and%20recovering,UN%20Environment%20Programme%20(UNEP) (accessed on 2 January 2025).
25. Barbieri, P.; MacDonald, G.K.; Bernard de Raymond, A.; Nesme, T. Food system resilience to phosphorus shortages on a telecoupled planet. *Nat. Sustain.* **2021**, *5*, 114–122. [CrossRef]
26. Beck, S.; Jasanoff, S.; Stirling, A.; Polzin, C. The governance of sociotechnical transformations to sustainability. *Curr. Opin. Environ. Sustain.* **2021**, *49*, 143–152. [CrossRef]
27. Vormedal, I.; Bjander, J.; Larsen, M.L.; Lindberg, M.B. Technological Change and the Politics of Decarbonization: A Re-making of Vested Interests? *Environ. Innov. Soc. Transit.* **2023**, *47*, 100725. [CrossRef]
28. Gesing, F. The material politics of slurry: Mobilisations and transformations along the waste–fertiliser continuum. *Polit. Geogr.* **2023**, *101*, 102832. [CrossRef]
29. Lucas, E.; Kennedy, B.; Roswall, T.; Burgis, C.; Toor, G.S. Climate Change Effects on Phosphorus Loss from Agricultural Land to Water: A Review. *Curr. Pollut. Rep.* **2023**, *9*, 623–645. [CrossRef]
30. Shiroyama, H.; Yarime, M.; Matsuo, M.; Schroeder, H.; Scholz, R.; Ulrich, A.E. Governance for sustainability: Knowledge integration and multi-actor dimensions in risk management. *Sustain. Sci.* **2012**, *7*, 45–55. [CrossRef]
31. Hoppe, T.; Kuokkanen, A.; Mikkilä, M.; Kahiluoto, H.; Kuisma, M.; Arentsen, M.; Linnanen, L. System merits or failures? Policies for transition to sustainable P and N systems in the Netherlands and Finland. *Sustainability* **2016**, *8*, 463. [CrossRef]
32. Kuokkanen, A.; Mikkilä, M.; Kahiluoto, H.; Kuisma, M.; Linnanen, L. Not only peasants' issue Stakeholders perceptions of failures inhibiting system innovation in nutrient economy. *Environ. Innov. Soc. Transit.* **2016**, *20*, 75–85. [CrossRef]
33. Jacobs, B.; Cordell, D.; Chin, J.; Rowe, H. Towards phosphorus sustainability in North America: A model for transformational change. *Environ. Sci. Policy* **2017**, *77*, 151–159. [CrossRef]
34. UN. Brundtland Report of the World Commission on Environment and Development: Our Common Future. 1987. Available online: https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf (accessed on 2 January 2025).
35. Hajer, M.A. The Politics of Environmental Discourse. In *The Politics of Environmental Discourse*; Oxford University Press: Oxford, UK, 1997.
36. Houlton, B.Z.; Almaraz, M.; Aneja, V.; Austin, A.T.; Bai, E.; Cassman, K.G.; Compton, J.E.; Davidson, E.A.; Erisman, J.W.; Galloway, J.N.; et al. A World of Cobenefits: Solving the Global Nitrogen Challenge. *Earth's Future* **2019**, *7*, 865–872. [CrossRef] [PubMed]
37. Raustiala, K.; Victor, D.G. The regime complex for plant genetic resources. *Int. Organ.* **2004**, *58*, 277–309. [CrossRef]
38. Maslin, M.; Van Heerde, L.; Day, S. Sulfur: A potential resource crisis that could stifle green technology and threaten food security as the world decarbonises. *Geogr. J.* **2022**, *188*, 498–505. [CrossRef]
39. Tonelli, D.; Rosa, L.; Gabrielli, P.; Parente, A.; Contino, F. Cost-competitive decentralized ammonia fertilizer production can increase food security. *Nat. Food* **2024**, *5*, 469–479. [CrossRef] [PubMed]
40. Damro, C. Market power Europe. *J. Eur. Public Policy* **2012**, *19*, 682–699. [CrossRef]
41. Bradford, A. *The Brussels Effect: How the European Union Rules the World*; OUP: New York, NY, USA, 2020.
42. Damro, C. Market Power Europe and new EU trade policies. In *Global Governance through Trade*; Edward Elgar Publishing: Northampton, MA, USA, 2015. [CrossRef]
43. Magacho, G.; Espagne, E.; Godin, A. Impacts of the CBAM on EU trade partners: Consequences for developing countries. *Clim. Policy* **2024**, *24*, 243–259. [CrossRef]
44. Vogler, J.; Stephan, H.R. The European Union in global environmental governance: Leadership in the making? *Int. Environ. Agreem.* **2007**, *7*, 389–413. [CrossRef]

45. Fraundorfer, M.; Winn, N. The emergence of post-Westphalian health governance during the COVID-19 pandemic: The European Health Union. *Disasters* **2021**, *45*, S5–S25. [CrossRef] [PubMed]
46. Walsh, M.; Schenk, G.; Schmidt, S. Realising the circular phosphorus economy delivers for sustainable development goals. *NPJ Sustain. Agric.* **2023**, *1*, 2. [CrossRef]
47. Bevir, M. *The SAGE Handbook of Governance*; SAGE Publications Ltd.: London, UK, 2011.
48. Levi-Faur, D. From "Big Government" to "Big Governance"? Oxford University Press: Oxford, UK, 2012.
49. Anheier, H.; Fliegauf, M. Governance Challenges and Innovations. In *Governance Challenges and Innovations*; Oxford University Press: Oxford, UK, 2013; pp. 136–169.
50. Weber, K.M.; Rohracher, H. Legitimizing research, technology and innovation policies for transformative change. *Res. Policy* **2012**, *41*, 1037–1047. [CrossRef]
51. Mazzucato, M. *Governing Missions in the European Union*; European Union DG Research and Innovation: Brussels, Belgium, 2019; pp. 1–32. [CrossRef]
52. Hekkert, M.P.; Janssen, M.J.; Wesseling, J.H.; Negro, S.O. Mission-oriented innovation systems. *Environ. Innov. Soc. Transit.* **2020**, *34*, 76–79. [CrossRef]
53. Simpson, S. 'New' Governance in European Union Policy Making: Policy Innovation or Political Compromise in European Telecommunications? *West Eur. Polit.* **2011**, *34*, 1114–1133. [CrossRef]
54. Casula, M. Implementing the transformative innovation policy in the European Union: How does transformative change occur in Member States? *Eur. Plan. Stud.* **2022**, *30*, 2178–2204. [CrossRef]
55. Boyd, B.; Lorefice, S. Understanding consultation and engagement of Indigenous Peoples in resource development: A policy framing approach. *Can. Public Adm.* **2018**, *61*, 572–595. [CrossRef]
56. Goffman, E. *Frame Analysis: An Essay on the Organization of Experience*; Harvard University Press: Cambridge, MA, USA, 1974.
57. Tversky, A.; Kahneman, D. The Framing of Decisions and the Psychology of Choice. *Science* **1981**, *211*, 453–458. [CrossRef]
58. Snow, D.A.; Burke Rochford, E.; Worden, S.K. Frame Alignment Processes, Micromobilization, and Movement Participation. *Am. Sociol. Rev.* **1986**, *51*, 464–481. Available online: https://www.researchgate.net/publication/246234920_Frame_Alignment_Process_Micromobilization_and_Movement_Participation (accessed on 2 January 2025). [CrossRef]
59. Entman, R.M. Framing: Toward Clarification of a Fractured Paradigm. *J. Commun.* **1993**, *43*, 51–58. [CrossRef]
60. Rein, M.; Schoen, D. Frame-Critical Policy Analysis and Frame-Reflective Policy Practice. *Knowl. Technol. Policy* **1996**, *9*, 85–104. [CrossRef]
61. Dewulf, A.; Bouwen, R. Issue Framing in Conversations for Change. *J. Appl. Behav. Sci.* **2012**, *48*, 168–193. [CrossRef]
62. Olsen, A. Equivalency Framing in Political Decision Making. In *Oxford Research Encyclopedia of Politics*; Oxford University Press: Oxford, UK, 2020. [CrossRef]
63. Oxley, Z. Framing and Political Decision Making: An Overview. In *Oxford Research Encyclopedia of Politics*; Redlawsk, D.P., Ed.; Oxford University Press: Oxford, UK, 2020.
64. Daviter, F. *Policy Framing in the European Union*; Palgrave Macmillan: London, UK, 2011.
65. Vaz, F.; Koria, M.; Prendeville, S. 'Design for policy' from below: Grassroots framing and political negotiation. *Policy Des. Pract.* **2022**, *5*, 410–426. [CrossRef]
66. Vogeler, C.S.; Möck, M.; Bandelow, N.C. Shifting governance cooperatively—Coordination by public discourses in the German water-food nexus. *J. Environ. Manag.* **2021**, *286*, 112266. [CrossRef]
67. Fairclough, N. *Language and Power*; Longman Inc.: New York, NY, USA, 1996.
68. Carnahan, D.; Hao, Q.; Yan, X. Framing Methodology: A Critical Review. In *Oxford Research Encyclopedia of Politics*; Oxford University Press: Oxford, UK, 2019.
69. van Hulst, M.; Yanow, D. From Policy "Frames" to "Framing". *Am. Rev. Public Adm.* **2016**, *46*, 92–112. [CrossRef]
70. Kingdon, J. *Agendas, Alternatives, and Public Policies*; Pearson: London, UK, 2013.
71. Hoefer, R. The Multiple Streams Framework: Understanding and Applying the Problems, Policies, and Politics Approach. *J. Policy Pract. Res.* **2022**, *3*, 1–5. [CrossRef]
72. Eckersley, P.; Lakoma, K. Straddling multiple streams: Focusing events, policy entrepreneurs and problem brokers in the governance of English fire and rescue services. *Policy Stud.* **2022**, *43*, 1001–1020. [CrossRef]
73. Birkland, T.A. Focusing Events, Mobilization, and Agenda Setting. *J. Public Policy* **1998**, *18*, 53–74. [CrossRef]
74. Herweg, N. Explaining European agenda-setting using the multiple streams framework: The case of European natural gas regulation. *Policy Sci.* **2016**, *49*, 13–33. [CrossRef]
75. Becker, P. The reform of European cohesion policy or how to couple the streams successfully. *J. Eur. Integr.* **2019**, *41*, 147–168. [CrossRef]
76. Zahariadis, N. Ambiguity and choice in European public policy. *J. Eur. Public Policy* **2008**, *15*, 514–530. [CrossRef]
77. Maltby, T. European Union energy policy integration: A case of European Commission policy entrepreneurship and increasing supranationalism. *Energy Policy* **2013**, *55*, 435–444. [CrossRef]

78. Leppänen, T.; Liefferink, D. Agenda-setting, policy formulation, and the EU institutional context: The case of the Just Transition Fund. *Eur. Policy Anal.* **2022**, *8*, 51–67. [CrossRef]
79. Valin, N.; Huitema, D. Experts as policy entrepreneurs: How knowledge can lead to radical environmental change. *Environ. Sci. Policy* **2023**, *142*, 21–28. [CrossRef]
80. Zahariadis, N. *Ambiguity and Choice in Public Policy: Political Decision Making in Modern Democracies*; Georgetown University Press: Washington, DC, USA, 2003.
81. Herweg, N.; Huß, C.; Zohlnhöfer, R. Straightening the three streams: Theorising extensions of the multiple streams framework. *Eur. J. Political Res.* **2015**, *54*, 435–449. [CrossRef]
82. Øvald, C.B. Advancing the multiple streams framework for decision-making: The case of integrating ethics into the Norwegian oil fund strategy. *Policy Sci.* **2024**, *57*, 125–144. [CrossRef]
83. Haas, P.M. Introduction: Epistemic communities and international policy coordination. *Int. Organ.* **1992**, *46*, 1–35. [CrossRef]
84. Mukherjee, I.; Howlett, M. Who Is a Stream? Epistemic Communities, Instrument Constituencies and Advocacy Coalitions in Public Policy-Making. *Politics Gov.* **2015**, *3*, 65–75. [CrossRef]
85. Fletcher, A.L. Clearing the air: The contribution of frame analysis to understanding climate policy in the United States. *Environ. Politics* **2009**, *18*, 800–816. [CrossRef]
86. Ekman Burgman, L.; Wallsten, B. Should the Sludge Hit the Farm?—How Chemo-Social Relations Affect Policy Efforts to Circulate Phosphorus in Sweden. *Sustain. Prod. Consum.* **2021**, *27*, 1488–1497. [CrossRef]
87. Richardson, J.E.; Flowerdew, J. *Flowerdew & Richardson: The Routledge Handbook of Critical Discourse Studies*; Sage: Hemet, CA, USA, 2008.
88. Moon, K.; Blackman, D. A Guide to Understanding Social Science Research for Natural Scientists. *Conserv. Biol.* **2014**, *28*, 1167–1177. [CrossRef] [PubMed]
89. Bowen, G.A. Document Analysis as a Qualitative Research Method. *Qual. Res. J.* **2009**, *9*, 27–40. [CrossRef]
90. Carter, N.; Bryant-Lukosius, D.; DiCenso, A.; Blythe, J.; Neville, A.J. The Use of Triangulation in Qualitative Research. *Oncol. Nurs. Forum* **2014**, *41*, 545–547. [CrossRef] [PubMed]
91. Bolukbasi, H.T.; Yıldırım, D. Institutions in the politics of policy change: Who can play, how they play in multiple streams. *J. Public Policy* **2022**, *42*, 509–528. [CrossRef]
92. Häggmark, T.; Elofsson, K. The Impact of Water Quality Management Policies on Innovation in Nitrogen and Phosphorus Technology. *Water Econ. Policy* **2021**, *7*, 2150002. [CrossRef]
93. Fitch-Roy, O.; Benson, D.; Monciardini, D. Going around in circles? *Environ. Politics* **2020**, *29*, 983–1003. [CrossRef]
94. Hellsmark, H.; Hansen, T. A new dawn for (oil) incumbents within the bioeconomy? Trade-offs and lessons for policy. *Energy Policy* **2020**, *145*, 111763. [CrossRef]
95. Magnusson, T.; Werner, V. Conceptualisations of incumbent firms in sustainability transitions: Insights from organisation theory and a systematic literature review. *Bus Strategy Environ.* **2023**, *32*, 903–919. [CrossRef]
96. Novalia, W.; Malekpour, S. Theorising the role of crisis for transformative adaptation. *Environ. Sci. Policy* **2020**, *112*, 361–370. [CrossRef]
97. Arksey, H.; O'Malley, L. Scoping studies: Towards a methodological framework. *Int. J. Soc. Res. Methodol.* **2005**, *8*, 19–32. [CrossRef]
98. Levac, D.; Colquhoun, H.; O'brien, K.K. Scoping studies: Advancing the methodology. *Implement. Sci.* **2010**, *5*, 69. [CrossRef] [PubMed]
99. Galego, D.; Moulaert, F.; Brans, M.; Santinha, G. Social innovation & governance: A scoping review. *Innov. Eur. J. Soc. Sci. Res.* **2022**, *35*, 265–290. [CrossRef]
100. Wilson, V Research Methods: Scoping Studies. *EBLIP* **2014**, *9*, 97–99. [CrossRef]
101. Moon, K.; Brewer, T.D.; Januchowski-Hartley, S.R.; Adams, V.M.; Blackman, D.A. A guideline to improve qualitative social science publishing in ecology and conservation journals. *Ecol. Soc.* **2016**, *21*, 17. [CrossRef]
102. Busetto, L.; Wick, W.; Gumbinger, C. How to use and assess qualitative research methods. *Neurol. Res. Pract.* **2020**, *2*, 14. [CrossRef]
103. UNCTAD. *Memorandum of Understanding between the Russian Federation and the Secretariat of the United Nations on Promoting Russian Food Products and Fertilizers to the World Markets; Geneva, Switzerland*. 2022. Available online: https://unctad.org/system/files/information-document/MOU_21_July_UN-Secretariat86.pdf (accessed on 2 January 2025).
104. Commission/Council. *Council Regulation (EU) 2022/2465 of 12 December 2022 amending Annex I to Regulation (EEC) No 2658/87 on the Tariff and Statistical Nomenclature and on the Common Customs Tariff*. 2022. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32022R2465 (accessed on 2 January 2025).
105. Fertilisers Europe: Decarbonizing Fertilisers and Food European Fertilizer Industry's Ambition. 2023. Available online: https://www.fertilizerseurope.com/decarbonising-fertilizers-by-2050/ (accessed on 2 January 2025).

106. Fertilisers Europe: Decarbonising Fertilizers by 2050 The Industry's Roadmap Towards Climate Neutrality. 2023. Available online: https://www.fertilizerseurope.com/wp-content/uploads/2023/11/DEF_2023_Decarbonisation_Roadmap_digital.pdf (accessed on 2 January 2025).
107. EBA: European Biogas Association's Biomethane Fact Sheet. 2013. Available online: https://www.europeanbiogas.eu/wp-content/uploads/files/2013/10/eba_biomethane_factsheet.pdf (accessed on 2 January 2025).
108. Chauvy, R.; Dubois, L.; Lybaert, P.; Thomas, D.; De Weireld, G. Production of synthetic natural gas from industrial carbon dioxide. *Appl. Energy* **2020**, *260*, 114249. [CrossRef]
109. Bärnthaler, R.; Gough, I. Provisioning for sufficiency: Envisaging production corridors. *Sustain. Sci. Pract. Policy* **2023**, *19*, 2218690. [CrossRef]
110. AGRI: Analytical Brief 3: Explore Farm Incomes in the EU. Farm Economics Overview Based on 2021 FADN Data. November 2023. Available online: https://agriculture.ec.europa.eu/document/download/bc9e6d8c-5450-4c3a-884e-7198b44e371a_en?filename=analytical-brief-3-feo-brief_en.pdf (accessed on 2 January 2025).
111. Negre, F. Fact Sheets on the European Union: Direct Payments. Available online: https://www.europarl.europa.eu/factsheets/en/sheet/109/first-pillar-of-the-common-agricultural-policy-cap-ii-direct-payments-to-farmers (accessed on 2 January 2025).
112. EC (European Commission). *State Aid: Dutch Phosphate Rights Trading System Approved*; EC (European Commission): Brussels, Belgium, 2017.
113. Nedelciu, C.E.; Ragnarsdóttir, K.V.; Stjernquist, I. From waste to resource: A systems dynamics and stakeholder analysis of phosphorus recycling from municipal wastewater in Europe. *Ambio* **2019**, *48*, 741–751. [CrossRef]
114. Svanbäck, A.; McCrackin, M.L.; Swaney, D.P.; Linefur, H.; Gustafsson, B.G.; Howarth, R.W.; Humborg, C. Reducing agricultural nutrient surpluses in a large catchment—Links to livestock density. *Sci. Total Environ.* **2019**, *648*, 1549–1559. [CrossRef]
115. Peterson, C.A.; Deiss, L.; Gaudin, A.C.M. Commercial integrated crop-livestock systems achieve comparable crop yields to specialized production systems: A meta-analysis. *PLoS ONE* **2020**, *15*, e0231840. [CrossRef]
116. Justizamt. Verordnung über die Verwertung von Klärschlamm, Klärschlammgemisch und Klärschlammkompost (Klärschlammverordnung-AbfKlärV). Available online: https://www.gesetze-im-internet.de/abfkl_rv_2017/AbfKl%C3%A4rV.pdf (accessed on 2 January 2025).
117. Santos, A.F.; Almeida, P.V.; Alvarenga, P.; Gando-Ferreira, L.M.; Quina, M.J. From wastewater to fertilizer products: Alternative paths to mitigate phosphorus demand in European countries. *Chemosphere* **2021**, *284*, 131258. [CrossRef]
118. Water4All: Wastewater: Recover Vivianite Mineral, from Lab to Pilot Scale-with Wetsus Partner. Available online: https://www.water4all-partnership.eu/news/wastewater-recover-vivianite-mineral-lab-pilot-scale-wetsus-partner (accessed on 2 January 2025).
119. Aimforclimate: Agricultural Innovation Mission for Climate Innovation Sprint Framework, (2024). Available online: https://www.aimforclimate.org/media/ym0fdw2c/2024-isp-framework.pdf (accessed on 2 January 2025).
120. FAO: The 10 Elements of Agroecology Guiding the Transition to Sustainable Food and Agricultural Systems. Available online: https://openknowledge.fao.org/server/api/core/bitstreams/3d7778b3-8fba-4a32-8d13-f21dd5ef31cf/content (accessed on 2 January 2025).
121. ESPP: SCOPE Newsletter 151: Market "Pull" Policies for Uptake of Recycled Nutrients, (2024). Available online: https://www.phosphorusplatform.eu/images/scope/ScopeNewsletter151.pdf (accessed on 2 January 2025).
122. Mingolla, S.; Gabrielli, P.; Manzotti, A.; Robson, M.J.; Rouwenhorst, K.; Ciucci, F.; Sansavini, G.; Klemun, M.M.; Lu, Z. Effects of emissions caps on the costs and feasibility of low-carbon hydrogen in the European ammonia industry. *Nat. Commun.* **2024**, *15*, 3753. [CrossRef]
123. Negro, V.; Noussan, M.; Chiaramonti, D. The Potential Role of Ammonia for Hydrogen Storage and Transport: A Critical Review of Challenges and Opportunities. *Energies* **2023**, *16*, 6192. [CrossRef]
124. Røyne, A. The Economics of Nitrogen Fertilizer in the Green Transition. Master's Thesis, University of Oslo, Oslo, Norway, 2023. Available online: https://www.duo.uio.no/bitstream/handle/10852/103348/RoyneMaster2023.pdf?sequence=1&isAllowed=y (accessed on 2 January 2025).
125. Rosa, L.; Gabrielli, P. Energy and food security implications of transitioning synthetic nitrogen fertilizers to net-zero emissions. *Environ. Res. Lett.* **2023**, *18*, 014008. [CrossRef]
126. Dwyer, O. Carbonbrief Analysis: How do the EU Farmer Protests Relate to Climate Change? 2024. Available online: https://www.carbonbrief.org/analysis-how-do-the-eu-farmer-protests-relate-to-climate-change/ (accessed on 2 January 2025).
127. Garske, B.; Heyl, K.; Ekardt, F. The EU Communication on ensuring availability and affordability of fertilisers—A milestone for sustainable nutrient management or a missed opportunity? *Environ. Sci. Eur.* **2024**, *36*, 19. [CrossRef]
128. Moore, O.; Parsons, A. EU Fertilizer Industry Wins Big in Commission Communication. ARC 2020; 2022.15.10. Available online: https://www.arc2020.eu/eu-fertilizer-industry-wins-big-in-commission-communication/ (accessed on 2 January 2025).
129. The Institute for Agriculture and Trade Policy, The Fertilizer Trap. 2022, Nov 8. Available online: https://www.iatp.org/the-fertiliser-trap (accessed on 2 January 2025).

130. Armstrong, K.A. The Open Method Of Coordination: Obstinate Or Obsolete? In *Oxford Principles Of European Union Law: The European Union Legal Order: Volume I*; Oxford University Press: Oxford, UK, 2018.
131. EU. Strategic Dialogue on the Future of EU Agriculture: A Shared Prospect for Farming and Food in Europe. Available online: https://agriculture.ec.europa.eu/document/download/171329ff-0f50-4fa5-946f-aea11032172e_en?filename=strategic-dialogue-report-2024_en.pdf (accessed on 2 January 2025).
132. EC. The European Commission 2024-2029 Our Priorities for Europe's Strength and Unity. Available online: https://ec.europa.eu/stories/2024-2029-commission/ (accessed on 2 January 2025).
133. COM(2024)63: Securing Our Future Europe's 2040 Climate Target and Path to Climate Neutrality by 2050 Building a Sustainable, Just and Prosperous Society. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52024DC0063 (accessed on 2 January 2025).
134. von der Leyen, U. Statement at the European Parliament Plenary by President Ursula von der Leyen, Candidate for a Second Mandate 2024–2029; Brussels, Belgium. 2024. Available online: https://ec.europa.eu/commission/presscorner/detail/ov/STATEMENT_24_3871 (accessed on 2 January 2025).
135. *Parliament/Council: Regulation (EU) 2024/1252 of the European Parliament and of the Council of 11 April 2024 Establishing a Framework for Ensuring a Secure and Sustainable Supply of Critical Raw Materials*; EUR-Lex: Brussels, Belgium, 2024.
136. TCOcertified: Circular Electronics Initiative: 12 Percent Circular Material Use in EU—Sustainable Use of IT Products Can Make a Big Difference, (2023). Available online: https://tcocertified.com/pressrelease/12-percent-circular-material-use-in-eu-sustainable-use-of-it-products-can-make-a-big-difference/ (accessed on 2 January 2025).
137. Consilium: Council of the EU: Strategic agenda 2024–2029, (2024). Available online: https://www.consilium.europa.eu/media/yxrc05pz/sn02167en24_web.pdf (accessed on 2 January 2025).
138. Global Counsel. The next European Political Cycle. 2023. Available online: https://6008785.fs1.hubspotusercontent-na1.net/hubfs/6008785/The%20next%20European%20Political%20Cycle%20vf.pdf (accessed on 15 April 2023).
139. Dennison, S. European Council on Foreign Relations. 2024, February 20. Agricultural Tackles: Protesting Farmers and the EU's Climate Agenda. Available online: https://ecfr.eu/article/agricultural-tackles-protesting-farmers-and-the-eus-climate-agenda/ (accessed on 2 January 2025).
140. Weckroth, M.; Faure, G.; Siddi, M.; Niemi, J.; Karttunen, K.; Rasa, K.; Stephani, T.; Pitkäinen, V.; Hakala, M. Nutrient recycling in the grip of geopolitics. Finnish Institute of International Affairs (FIIA). Available online: https://fiia.fi/en/tapahtumat/nutrient-recycling-in-the-grip-of-geopolitics (accessed on 2 January 2025).
141. Liu, Z.; Yin, X.; Ni, B.; Chen, X.; Xie, F.; Guo, Z.; Li, D.; Liu, W.; Yue, X.; Zhou, A. Synchronous vivianite and hydrogen recovery from waste activated sludge fermentation liquid via electro-fermentation mediated by iron anode. *Chem. Eng. J.* **2023**, *474*, 145442. [CrossRef]
142. Holatko, J.; Brtnicky, M.; Mustafa, A.; Kintl, A.; Skarpa, P.; Ryant, P.; Baltazar, T.; Malicek, O.; Latal, O.; Hammerschmiedt, T. Effect of Digestate Modified with Amendments on Soil Health and Plant Biomass under Varying Experimental Durations. *Materials* **2023**, *16*, 1027. [CrossRef]
143. Enebe, N.L.; Chigor, C.B.; Obileke, K.; Lawal, M.S.; Enebe, M.C. Biogas and Syngas Production from Sewage Sludge: A Sustainable Source of Energy Generation. *Methane* **2023**, *2*, 192–217. [CrossRef]
144. Wu, Y.; Luo, J.; Zhang, Q.; Aleem, M.; Fang, F.; Xue, Z.; Cao, J. Potentials and challenges of phosphorus recovery as vivianite from wastewater: A review. *Chemosphere* **2019**, *226*, 246–258. [CrossRef]
145. European Commission. *Criteria for the Analysis of the Compatibility with the Internal Market of State Aid to Promote the Execution of Important Projects of Common European Interest (2014/C 188/02)*; European Commission: Brussels, Belgium, 2014.
146. Dedecca, J.G.; Ansarin, M.; Afrodit Adsal, K.; Blind, K. *Regulatory Sandboxes in the Energy Sector*; EU: Brussels, Belgium, 2023. [CrossRef]
147. European Commission. *Questions and Answers on the Net-Zero Industry Act*; European Commission: Brussels, Belgium, 2024.
148. von der Leyen, U. Mission Letter to Ekaterina Zaharieva Commissioner-Designate for Startups, Research and Innovation, (2024). Available online: https://commission.europa.eu/document/download/833e082a-0c39-4bc6-a119-e0760ebc7360_en?filename=mission-letter-zaharieva.pdf (accessed on 2 January 2025).
149. Efthymiou, V.; Hartz, N.; McGranaghan, M.; Schulz, M.; Kreusel, J.; Almeida Henriques, R.; Morch, A.; Jarásová, D.; Stanev, R.; Dimeas, A.; et al. Regulatory Sandboxes–Policy report Drafted by WG5's Regulatory Sandboxes Task Force. 2023. Available online: https://op.europa.eu/en/publication-detail/-/publication/d74556a2-4ba0-11ee-9220-01aa75ed71a1/language-en (accessed on 2 January 2025).
150. Carrez, D.; Rupp, M. A Thriving Bioeconomy Needs Better Tools for Measuring and Monitoring. *EuroChoices* **2023**, *22*, 51–55. [CrossRef]
151. World Bank: Global Experiences from Regulatory Sandboxes; Washington, DC, USA. 2020. Available online: https://documents1.worldbank.org/curated/en/912001605241080935/pdf/Global-Experiences-from-Regulatory-Sandboxes.pdf (accessed on 2 January 2025).

152. Aydın, Z.; Yardımcı, O. Regulatory sandboxes and pilot projects: Trials, regulations, and insights in energy transition. *Eng. Sci. Technol. Int. J.* **2024**, *56*, 101792. [CrossRef]
153. Leimüller, G.; Wasserbacher-Schwarzer, S. Regulatory Sandboxes: Analytical paper for Business Europe. 2020. Available online: https://www.businesseurope.eu/sites/buseur/files/media/other_docs/regulatory_sandboxes_-_winnovation_analytical_paper_may_2020.pdf (accessed on 2 January 2025).
154. Engelmann, W. Governance and Sandbox: Building Self-Regulation Models for Nanotechnologies. *J. Entrep. Res.* **2023**, *1*, 13–20. [CrossRef]
155. Schacherer, S. The Agility Paradigm: Rethinking Regulatory Policy Commitments in Free Trade Agreements. *J. World Trade* **2025**, *59*, 53–76. [CrossRef]
156. Nicastro, R.; Papale, M.; Fusco, G.M.; Capone, A.; Morrone, B.; Carillo, P. Legal Barriers in Sustainable Agriculture: Valorization of Agri-Food Waste and Pesticide Use Reduction. *Sustainability* **2024**, *16*, 8677. [CrossRef]
157. Kacprzak, M.; Kupich, I.; Jasinska, A.; Fijalkowski, K. Bio-Based Waste' Substrates for Degraded Soil Improvement—Advantages and Challenges in European Context. *Energies* **2022**, *15*, 385. [CrossRef]
158. Gianico, A.; Braguglia, C.; Gallipoli, A.; Montecchio, D.; Mininni, G. Land Application of Biosolids in Europe: Possibilities, Con-Straints and Future Perspectives. *Water* **2021**, *13*, 103. [CrossRef]
159. ESPP: Recovered Struvite Authorised in EU Certified Organic Farming, (2023). Brussels, Belgium. Available online: https://www.phosphorusplatform.eu/scope-in-print/news/2306-recovered-struvite-authorised-in-eu-certified-organic-farming (accessed on 2 January 2025).
160. Štrubelj, L. Waste, Fertilising Product, or Something Else? EU Regulation of Biochar. *J. Environ. Law* **2022**, *34*, 529–540. [CrossRef]
161. EU Commission Directorate-General for Agriculture and Rural Developmen. Fertiliser Market Observatory: Fertiliser Production. Available online: https://agridata.ec.europa.eu/extensions/DashboardFertiliser/FertiliserProduction.html (accessed on 2 January 2025).
162. ICAP. *EMISSIONS TRADING WORLDWIDE: Status Report*; ICAP: Mumbai, India, 2024.
163. Schröder, P.; Barrie, J. How the Circular Economy Can Revive the Sustainable Development Goals Priorities for Immediate Global Action, and a Policy Blueprint for the Transition to 2050; Chatham House; London, UK. 2024. Available online: https://www.chathamhouse.org/sites/default/files/2024-09/2024-09-19-how-the-circular-economy-can-revive-the-sdgs-schr%C3%B6der-barrie.pdf (accessed on 2 January 2025).
164. Lam, K.L.; Solon, K.; Jia, M.; Volcke, E.I.P.; van der Hoek, J.P. Life Cycle Environmental Impacts of Wastewater-Derived Phosphorus Products: An Agricultural End-User Perspective. *Environ. Sci. Technol.* **2022**, *56*, 10289–10298. [CrossRef]
165. Rani, A.; Snyder, S.W.; Kim, H.; Lei, Z.; Pan, S.-Y. Pathways to a net-zero-carbon water sector through energy-extracting wastewater technologies. *NPJ Clean Water* **2022**, *5*, 49. [CrossRef]
166. Qadir, M.; Drechsel, P.; Jiménez Cisneros, B.; Kim, Y.; Pramanik, A.; Mehta, P.; Olaniyan, O. Global and regional potential of wastewater as a water, nutrient and energy source. *Nat. Resour. Forum.* **2020**, *44*, 40–51. [CrossRef]
167. Salvetti, M. Going from energy efficiency to climate neutrality on the way to decarbonizing the wastewater sector. *Nat. Water* **2024**, *2*, 913–914. [CrossRef]
168. Song, C.; Zhu, J.-J.; Yuan, Z.; van Loosdrecht, M.C.M.; Ren, Z.J. Defining and achieving net-zero emissions in the wastewater sector. *Nat. Water* **2024**, *2*, 927–935. [CrossRef]
169. Song, C.; Zhu, J.-J.; Willis, J.L.; Moore, D.P.; Zondlo, M.A.; Ren, Z.J. Oversimplification and misestimation of nitrous oxide emissions from wastewater treatment plants. *Nat. Sustain.* **2024**, *7*, 1348–1358. [CrossRef]
170. Śniatała, B.; Al-Hazmi, H.E.; Sobotka, D.; Zhai, J.; Mąkinia, J. Advancing sustainable wastewater management: A comprehensive review of nutrient recovery products and their applications. *Sci. Total Environ.* **2024**, *937*, 173446. [CrossRef]
171. Zhu, F.; Cakmak, E.K.; Cetecioglu, Z. Phosphorus recovery for circular Economy: Application potential of feasible resources and engineering processes in Europe. *Chem. Eng. J.* **2023**, *454*, 140153. [CrossRef]
172. Korving, L.; Loosdrecht, M.; Van Wilfert, P. Effect of Iron on Phosphate Recovery from Sewage Sludge. In *Phosphorus Recovery and Recycling*; Springer: Singapore, 2019; pp. 303–326. [CrossRef]
173. Diaz, R.; Mackey, B.; Chadalavada, S.; kainthola, J.; Heck, P.; Goel, R. Enhanced Bio-P removal: Past, present, and future—A comprehensive review. *Chemosphere* **2022**, *309*, 136518. [CrossRef]
174. Consolidated Text: Council Directive of 21 May 1991 Concerning Urban Waste Water Treatment (91/271/EEC), (2014). Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:01991L0271-20140101 (accessed on 2 January 2025).
175. Bhandari, V.M.; Sorokhaibam, L.G.; Ranade, V.V. Industrial wastewater treatment for fertilizer industry—A case study. *Desalination Water Treat.* **2016**, *57*, 27934–27944. [CrossRef]
176. Li, J.; Li, X.; Liu, H.; Gao, L.; Wang, W.; Wang, Z.; Zhou, T.; Wang, Q. Climate change impacts on wastewater infrastructure: A systematic review and typological adaptation strategy. *Water Res.* **2023**, *242*, 120282. [CrossRef]

177. Al-Juboori, R.A.; Ahmed, F.E.; Khanzada, N.K.; Khatri, M.; Al-shaeli, M.; Ibrahim, Y.; Hilal, N. Burgeoning innovation and scalability activities for phosphorus recovery from wastewater treatment facilities. *Sustain. Mater. Technol.* **2024**, *40*, e00907. [CrossRef]
178. Egle, L.; Rechberger, H.; Krampe, J.; Zessner, M. Phosphorus recovery from municipal wastewater: An integrated comparative technological, environmental and economic assessment of P recovery technologies. *Sci. Total Environ.* **2016**, *571*, 522–542. [CrossRef]
179. Wijdeveld, W.K.; Prot, T.; Sudintas, G.; Kuntke, P.; Korving, L.; van Loosdrecht, M.C.M. Pilot-scale magnetic recovery of vivianite from digested sewage sludge. *Water Res.* **2022**, *212*, 118131. [CrossRef]
180. Serrano-Gomez, J.; Metson, G.S.; Neset, T.-S.; Santner, J.; Hermann, L.; Zessner, M. EU-compliant wastewater recycled phosphorus: How much national cereal demand can it meet? *J. Clean. Prod.* **2023**, *429*, 139482. [CrossRef]
181. Liu, H.; Kumar, V.; Yadav, V.; Guo, S.; Sarsaiya, S.; Binod, P.; Sindhu, R.; Xu, P.; Zhang, Z.; Pandey, A.; et al. Bioengineered biochar as smart candidate for resource recovery toward circular bio-economy: A review. *Bioengineered* **2021**, *12*, 10269–10301. [CrossRef]
182. Selvaraj, P.S.; Periasamy, K.; Suganya, K.; Ramadass, K.; Muthusamy, S.; Ramesh, P.; Bush, R.; Vincent, S.G.T.; Palanisami, T. Novel resources recovery from anaerobic digestates: Current trends and future perspectives. *Crit. Rev. Environ. Sci. Technol.* **2022**, *52*, 1915–1999. [CrossRef]
183. Tarpani, R.R.Z.; Azapagic, A. Life cycle sustainability assessment of advanced treatment techniques for urban wastewater reuse and sewage sludge resource recovery. *Sci. Total Environ.* **2023**, *869*, 161771. [CrossRef]
184. Huygens, D.; García-Gutierrez, P.; Orveillon, G.; Schillaci, C.; Delre, A.; Orgiazzi, A.; Wojda, P.; Tonini, D.; Egle, L.; Jones, A.; et al. Science for Policy Report Screening Risk Assessment of Organic Pollutants and Environmental Impacts From Sewage Sludge Management, Study to Support Policy Development on the Sewage Sludge Directive (86/278/EEC). 2022. Available online: https://publications.jrc.ec.europa.eu/repository/handle/JRC129690 (accessed on 2 January 2025).
185. Cherrier, V.; McAndrew, K.; Nicol, L.; Pandya, N.; Croad, B.; Madzharova, G.; Lavric, L.; Sendall, J.; Delacamara, G. *Support to the Evaluation of the Sewage Sludge Directive Exploratory Study—Final Report*; Publications Office of the European Union: Brussels, Belgium, 2022.
186. Bora, R.R.; Richardson, R.E.; You, F. Resource recovery and waste-to-energy from wastewater sludge via thermochemical conversion technologies in support of circular economy: A comprehensive review. *BMC Chem. Eng.* **2020**, *2*, 8. [CrossRef]

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Hydrogen Valley in Cyprus: Insights and Strategies for Citizen Engagement

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Abstract: In remote areas or islands like Cyprus, the isolated energy system, high energy consumption in the transport sector and projected excess electricity production from solar sources create favourable conditions for establishing a hydrogen valley. But even after addressing technological, managerial, economic and financial challenges, the success of a hydrogen valley hinges on the acceptance and engagement of the local population. The role of citizens is under-researched by academia and overlooked by policymakers. Our paper's contribution is unique data from a purposefully developed survey of Cypriot residents. The findings reveal robust support for the renewable energy transition in principle, with 90% expressing supportive views, of which 57% 'strongly support' the transition, and notably, middle-aged, more educated and fully employed individuals showing the strongest support. At the same time, our results show that 62% are unfamiliar with the concept of a hydrogen economy. The promising finding is that 80% of citizens are 'very likely' (25%) or 'somewhat likely' (55%) to engage in discussions or activities related to the creation of a hydrogen valley in Cyprus. Gender differences in the willingness to engage are, however, evident: 32% of males indicated they are 'very likely' to participate versus 23% of females. We conclude that the prevailing citizen behaviour in Cyprus is "Seeking Information", and we make policy suggestions outlining the top ten engagement tools to foster awareness among the general population and the top ten strategies targeting active supporters of hydrogen in Cyprus to elevate their involvement to 'Action' and 'Advocacy' levels of engagement.

Keywords: environmental policy; sustainability; hydrogen; hydrogen valley; citizen engagement; Cyprus; stakeholder engagement; environmental governance; technological transition

1. Introduction

The European Green Deal aspires to achieve carbon neutrality by 2050, positioning Europe as the first climate-neutral continent. Hydrogen, driven by its versatile properties and recent technological advancements, has become key for the European Union (EU) to achieve the green energy transition.

Hydrogen possesses numerous applications across industry, transport and building sectors. More importantly, hydrogen can be used as an energy carrier and storage medium. It can be produced through the electrolysis of water using electricity. During electrolysis, electricity is used to split water into hydrogen and oxygen, effectively storing the

energy in hydrogen. This hydrogen can be stored and transported, making hydrogen an energy carrier.

The ability of hydrogen to store and preserve energy offers a critical advantage over other counterparts, like the direct use of electricity coming from photovoltaics or wind turbines. While fossil fuels are in general both storable and transportable, their nature inherently limits long-term sustainability. In contrast, renewable energy sources, through their abundance, are intermittent and lack inherent storage and transportability. Hence, hydrogen meets all those challenges by converting renewable energy into storable and on-demand resources. The ultimate integrated target is to increase the share of hydrogen in Europe's energy mix from the current level of less than 2% to 13–14% by 2050 [1]. This implies that hydrogen should reach approximately one-seventh of the final energy consumption in 25 years.

The EU hydrogen policy framework introduces the concept of "Hydrogen Valleys", which are defined as localized hydrogen clusters, including remote areas, regional ecosystems or islands. These clusters will depend on local hydrogen production and consumption, with transportation confined to short distances. Beyond applications in industry and transport, hydrogen valleys will utilize hydrogen for electricity storage and grid balancing, as well as for heating/cooling residential and commercial buildings.

Cyprus is an island with no indigenous hydrocarbon energy sources (at least at the exploitation phase). Its energy grid is isolated, solely relying on a single vertically integrated utility, with no interconnections to neighbouring systems. The power generation system of the Republic of Cyprus heavily depends on imported fuels, which are primarily heavy fuel oil and gasoline, resulting in high CO_2 emissions.

Cyprus' Integrated National Energy and Climate Plan [2] necessitates a radical transformation of the energy system and requires the achievement of at least 23% renewable energy sources in final energy consumption towards 2030. The plan provides very promising projections for energy generation in Cyprus and shows that Cyprus can become a country exporting electricity produced from solar energy. The solar energy potential of Cyprus is approximately 3.5 times higher than the current electricity demand. Therefore, it becomes clear that Cyprus can produce more green electricity than required for its own needs [3,4].

The EU-wide strategic directions for green energy transition, bolstered by technological innovations, align well with the economic expediency of hydrogen implementation in Cyprus. The island's geographical constraints and the structure of its economy, which sees the highest energy consumption in the transport sector, make hydrogen an attractive solution. Additionally, the projected excess of electricity production from solar sources provides a viable pathway for green hydrogen production. These factors collectively originate favourable conditions for the creation of a hydrogen valley in Cyprus.

The green energy project for establishing the hydrogen valley in Cyprus necessitates addressing numerous technological, managerial, economic and financial challenges. However, the ultimate objective of a hydrogen valley is to enhance the lives of citizens. Therefore, the success of a hydrogen valley hinges on the awareness, acceptance and engagement of the local population.

Like other green energy projects, hydrogen valleys primarily deliver environmental benefits, which cannot always be effectively realized through traditional market mechanisms. As a result, public acceptance and citizen engagement are of vital importance. This article has two primary objectives:

- To examine the current state of citizen engagement with hydrogen technology in Cyprus;

- To propose key strategies for fostering citizen engagement in the development of a hydrogen valley in Cyprus.

Having conducted a hydrogen awareness survey of Cypriot residents, we have gained valuable insights into citizens' attitudes, awareness and willingness to engage with hydrogen initiatives. Our findings show strong support for the renewable energy transition and a high willingness to participate in hydrogen valley-related activities. Yet, this study also reveals that most of the population engages only at the weakest level, "Awareness", with prevailing citizen behaviour characterized as "Seeking information".

Using insights from survey data analysis, we propose tools for citizen engagement strategies related to a hydrogen valley in Cyprus. The latter is the main scientific contribution of this study, as it makes significant policy suggestions for the critical yet often overlooked aspect of hydrogen valleys: the role of citizens. By focusing on awareness, acceptance and engagement in Cyprus, an island with unique energy challenges and opportunities, this study offers practical strategies for involving people in hydrogen initiatives in other parts of the world. These insights may provide a blueprint that can be applied to similar projects across the globe.

In Section 2 of this article, we undertake a review of the existing literature on hydrogen valleys, with a particular focus on the role of citizen engagement in advancing green energy projects. In Section 3, we establish a framework for analysing the evolution of citizen engagement over time. This section also details the data collection process, including the design of survey instruments, research design and the employed methodology. Section 4 presents the findings from the statistical analysis of the survey data. This includes key findings and insights derived from the data. Section 5 delves into a discussion of the findings, linking them to broader theoretical and practical implications. Finally, Section 6 summarizes the study's main conclusions and outlines actionable recommendations and proposals for future research. This article emphasizes that policymakers must integrate technological deployment with coordinated and dynamic engagement frameworks. Additionally, this article includes two appendices: Appendix A outlines the range of hydrogen citizen engagement tools, and Appendix B includes the *p*-values for Fisher's exact test for the null hypotheses tested in this study, as well as pie charts that illustrate how respondents' answers to specific questions of interest differ across various demographic groups. Appendix C provides descriptive statistics of the hydrogen knowledge score variable.

2. Literature Review

European regions play a key role in building a hydrogen ecosystem and launching a clean hydrogen economy across the continent. The co-location of hydrogen suppliers with multiple end-users should foster the production of hydrogen and the development of the necessary infrastructure in the region. The hydrogen value chain holds the potential to drive sustainable regional development, foster economic growth and provide long-term employment opportunities. The concept of hydrogen valleys falls within this context. The purpose of hydrogen valleys is to "bring together clean hydrogen production, storage, distribution and end-use into fully functioning and sustainable local or regional value chains" [5].

The academic literature supports the idea of hydrogen valleys. For example, having analysed different aspects of the policy task for scaling up low-carbon hydrogen production in Europe, in particular the locality of hydrogen production (centralized vs. distributed), López et al. [6] conclude that hydrogen valleys seem to be the strategic approach. By generating localized "mini-economies", hydrogen valleys provide economic incentives, jobs, and advance decarbonization. Also, Vivanco-Martín et al. [7] (p. 9) highlighted that

"one main attraction of the hydrogen valleys is the fact that they are integrated systems; since they cover the value chain, they combine supply and demand".

Hydrogen valleys are often examined through cross-project analyses across multiple countries. For example, McWilliams et al. [8] emphasize the consistency of national strategies in Germany, Portugal and Poland with the hydrogen valley approach. Quitzow et al. [9] indicate that hydrogen valley initiatives are concentrated in high-capacity EU Member States, with lower activity in Eastern and Southeastern Europe. Wolf [10] points out regional heterogeneity and infrastructure limitations as challenges.

Additionally, Majka et al. [11] conducted a SWOT (strengths, weaknesses, opportunities and threats) analysis of hydrogen projects in various countries. They concluded that the nature of the area is a significant factor. In particular, the location of the valley in a small territory (island, province, country), particularly locations isolated from large industrial areas, and the need for energy autonomy can facilitate hydrogen valley development. The role of seaports is crucial, as Notteboom et al. [12] discuss the prerequisites for ports to succeed in supporting the green hydrogen economy. A country-wise analysis (or even a particular region) of hydrogen valleys can be found, for example, in [13–16], which analyse hydrogen valleys in Spain, Sweden, Italy and Greece. The hydrogen transformation of a country is an energy mega-project that requires careful consideration from multiple perspectives and the resolution of a wide range of complex, multidisciplinary questions. Research in this area, which often focuses on enhancing national energy and climate plans or providing a hydrogen transition roadmap, views hydrogen as a tool for industrial development and economic diversification. Governments are typically regarded as the primary drivers of hydrogen development, while citizen engagement, due to the complexity of the task, if mentioned at all, is often considered a secondary challenge to be addressed in the later stages of hydrogen implementation.

Hydrogen is vital for hydrogen valleys, supporting applications in transportation, industry and residential use. Proton exchange membrane fuel cells (PEMFCs) are key to its adoption, especially in transportation, requiring reliable and durable performance under dynamic conditions. Recent advances, such as deep learning and health index-based methods, have improved the accuracy of PEMFC health state estimation and lifetime prediction [17,18]. These innovations enhance reliability, fostering public trust and driving the transition to a sustainable hydrogen economy in hydrogen valleys.

In contrast, renewable energy sources, through their abundance, are intermittent and lack inherent storage and transportability. Hence, hydrogen meets all those challenges by converting renewable energy into storable and on-demand resources. Additionally, to solve the intermittent problems of renewable energy sources, Fe-based flow batteries are used for broad-scale energy storage, and they are also very safe and have zero emissions [19]. Hydrogen-based energy storage excels in large-scale, long-term use compared to batteries, which are efficient, safe and emission-free but limited to short-to-medium-term storage due to capacity and degradation issues. With higher energy density, hydrogen enables seasonal storage to address renewable energy variability and serves as both an energy carrier and industrial feedstock. Its transportability over long distances further decouples production from consumption. While safety and cost remain challenges, advancements in solid-state storage and low-cost electrolyser materials are enhancing hydrogen storage feasibility [20].

While hydrogen offers significant potential for energy storage and generation, degradation remains a key challenge, particularly for fuel cells. Over extended operational periods, fuel cells experience performance degradation due to complex operational conditions and component ageing, which limits their commercialization. The limited lifespan of fuel cells is a significant barrier, as their performance deteriorates over time, eventually reaching a threshold where they can no longer operate efficiently [21]. Therefore, it is

crucial to highlight these challenges, alongside the positive demonstrations of hydrogen technologies such as fuel cells and hydrogen refuelling stations, to ensure that the public is aware of both the potential and limitations of hydrogen-based solutions.

While the above literature examines the technological and economic aspects of hydrogen valleys in the EU, it quite often overlooks the societal impacts, like citizen awareness and engagement. For example, Frankowska et al. [22] (p. 357) concluded that the "management and coordination of Hydrogen Valleys, cooperation with stakeholders, and social aspects related to, among others, the issue of social acceptance of investments in hydrogen technologies" require additional research.

Among the literature focused specifically on citizen engagement in the hydrogen economy, the following mature publications (published a decade or so ago) can be mentioned: [23–25]. They contribute to the debates about citizen involvement in decisions about science and technological innovation. The studies argue that citizens should have an active role throughout the entire process of scientific research and development, and they should not be merely passive recipients of expert knowledge. The publications also highlight that the studies say relatively little about the wider role of the public and the role of different social interests in shaping the production of societal visions and technological expectations.

The topic of citizen engagement has received continued interest in the recent academic literature. "Establishing public engagement as a cornerstone of inclusive and sustainable governance of climate-intervention technologies" [26]. Citizens who are affected by a new technology should be directly involved in the planning, design, decision-making or knowledge-production process. As a result, citizens are no longer passive consumers or recipients of technology but are becoming empowered collective decision-makers.

Bănică et al. [27] conducted an interesting study on citizen engagement with sustainable energy solutions. They examined how various forms of perceived value—utilitarian, social and environmental—influence different citizen engagement behaviours.

Gordon et al. [28,29] started with the proposition that it is unclear whether consumers will be willing to adopt hydrogen-fuelled appliances for heating and cooking and demonstrate that a future research agenda should account for the interactions between acceptance factors at the attitudinal, socio-political, market, community and behavioural levels. "The analysis concludes that hydrogen is yet to permeate the public consciousness due to a lack of knowledge and awareness, owing to an absence of information dissemination" [28] (p. 1). The same authors in another paper on the 'deep' decarbonization of the residential sector propose a five-dimensional model of domestic hydrogen acceptance, which includes attitudinal, sociopolitical, community, market and behavioural acceptance [29].

BRIDGE, an initiative by the European Commission, supports research and innovation in smart energy systems across the EU. Citizen engagement is deemed a crucial element in the energy transition, and regular reports are published on exploring citizen engagement methodologies in European research and innovation projects [30–32].

Beauchampet et al. [33] studied the theory and practice of citizen engagement in the gas-free transition from a local government perspective. The authors used data collected during semi-structured interviews conducted with municipal officials to explore their understanding of citizen engagement.

Obenaus-Emler et al. [34] introduced a concept for interactive societal learning on hydrogen and carbon. To "strengthen the social licence to operate, the amalgamation of technological and wider society educational learning approaches unite to form a holistic front" [34].

Eliades et al. [35] emphasize that environmental and sustainability education is the first and most crucial stage in developing active and engaged local communities. They

explored the infrastructural aspects of citizen engagement and examined the establishment of environmental education centres in Cyprus and Greece as a key step in fostering social interaction and innovation to address sustainability challenges.

The current study contributes to the academic literature through empirical research on country-specific aspects, as well as cultural and socioeconomic factors influencing citizen engagement in hydrogen projects. It also offers approaches for developing citizen engagement strategies in hydrogen valley initiatives in Cyprus and beyond.

3. Materials and Methods

3.1. Conceptual Foundations

From the conceptual perspective, this study was performed at a country level and focused on Cyprus citizens, who were the object of the study, their hydrogen engagement, which was the subject of the study, and the wide application of hydrogen technology in Cyprus, which is the desired state to be achieved in the future.

The term "citizen" refers to inhabitants in their capacity for taking collective actions, playing an active role in the technology implementation and undertaking responsibilities (for themselves and others) for the societal governance of the energy system.

In the context of the transformation of the economy by hydrogen technology, citizens can be categorized as stakeholders of the hydrogen transformation, through a natural extension of the classical definition of organizations' stakeholders ("groups and individuals who can affect, or are affected by, the achievement of an organization's mission" [36]).

In addition to the usual external/internal segmentation of the stakeholders, for hydrogen transformation projects, stakeholders can be categorized as follows:

- Societal stakeholders: citizens, communities, consumers, prosumers, clients/end users;
- Utility-related stakeholders: technology providers, producers, suppliers and contractors, market operators, aggregators, entrepreneurs;
- Third-party stakeholders: government agencies, public authorities, NGOs, academia and research institutions, project partners, investors and financial institutions, environmental organizations and media.

The categorization and shaping of stakeholders are crucial for the strategic management of the hydrogen transformation of the economy because it requires balancing and addressing a wide range of stakeholder interests. Facilitating stakeholder engagement is a prerequisite for success. Specifically, citizen engagement is increasingly recognized as a key driver of the sustainable energy transition [27].

Stakeholder engagement is an attribute of stakeholders that reflects their attitude toward the mission. Engaged stakeholders are enthusiastic, committed and ready to invest time and effort in the project's mission, their relationship with the project and related activities.

Citizen engagement results in different forms of citizen behaviours: information seeking, proactive managing, sharing feedback, helping other users and advocating [27]. Citizen engagement is a process that evolves over time, and, thus, it may and should be managed by utility-related and third-party stakeholders.

Citizen engagement starts from zero (an attitude toward the mission has not been established yet) and can be positive or negative over time. The framework for the development of citizen engagement over time is presented in Figure 1. As a result of the information flow generated by utility-related and third-party stakeholders, citizens start to recognize that a new hydrogen technology has emerged. As the number of publications about hydrogen increases, the technology diffusion process intensifies, and citizens realize

the importance of the new technology and start deciding whether they are in favour or against hydrogen technology.

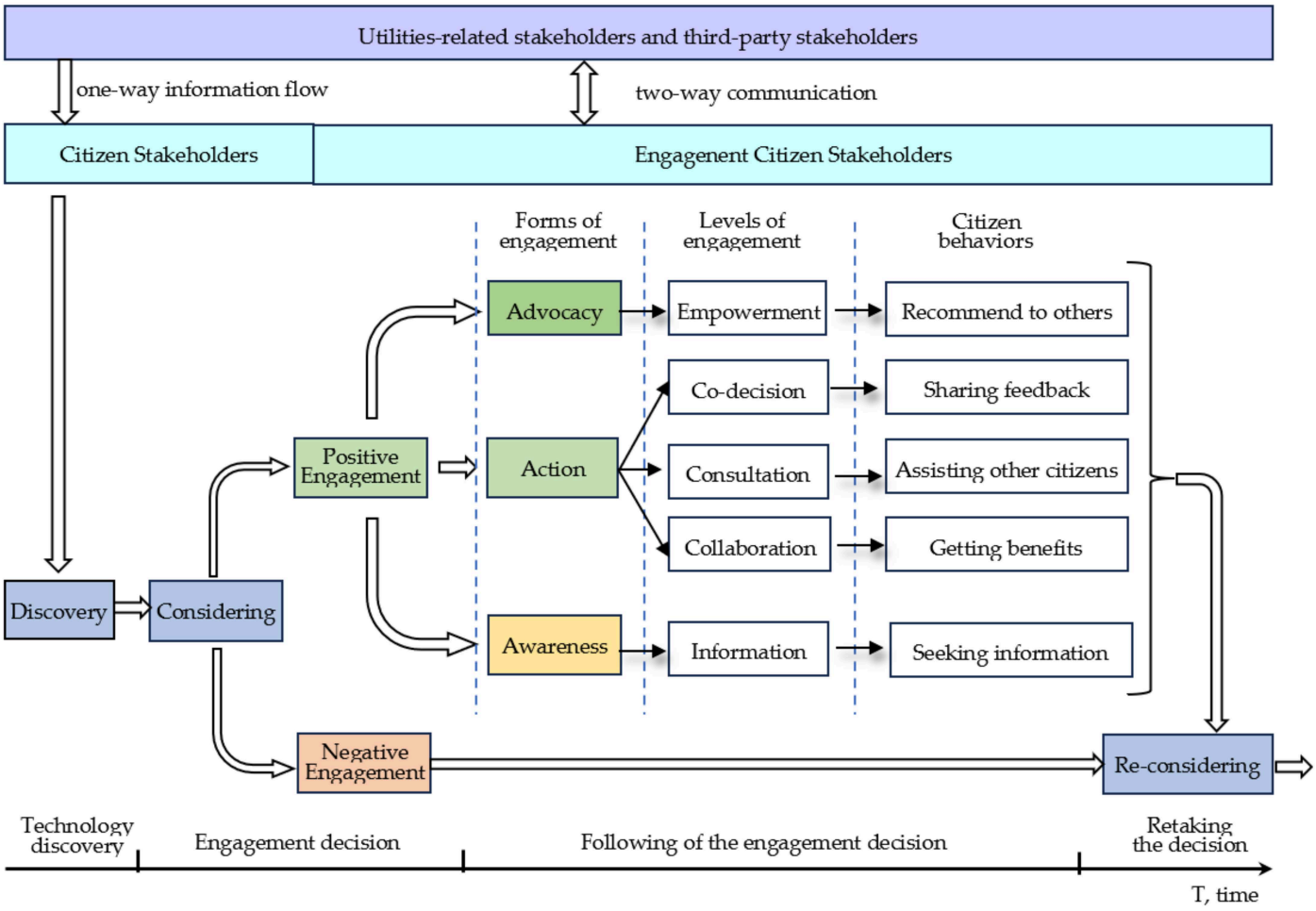


Figure 1. The framework for the development of citizen engagement over time.

The configuration of potential citizen responses can be described by the 'social acceptance matrix' [29,37,38]. The citizen reaction can be positive/negative over the attitude dimension and active/passive over the action dimension. The negative response (or negative engagement) can include disinterest, uncertainty, indifference, as well as apathy, resistance and opposition.

Positive engagement can take one of the "AAA" forms: awareness, action, advocacy, of which action and advocacy are active forms and awareness is passive. These forms of positive citizen engagement correspond to different levels of "Arnstein's ladder of citizen participation" [39] and citizen engagement behaviours [27] (Figure 1).

Approaching by citizens the "Engagement decision" stage (Figure 1), this facilitates the exchange of information between the public and policymakers—in terms of the model, between citizen stakeholders on one side, and utility-related stakeholders and third-party stakeholders on the other side. One-way information flow transforms into two-way communication as citizens seek more information to enhance their hydrogen awareness and begin to influence policymaking and other stakeholder decisions.

The involvement of citizens is realized through socially related engagement behaviours [27].

- Information-seeking behaviour. Citizens are focused on reducing uncertainty and better understanding hydrogen technology and related services. The examination of

learning efforts and exploring sources used by correspondents to obtain information about energy and environmental problems is one of the questions in the current study survey.

- Receiving-benefits behaviour. With knowledge of hydrogen technology, citizens try to maximize the benefits related to innovations at different levels, from individual to national.
- Assisting other citizens' behaviour. Helping behaviours stem from individuals' sense of social responsibility toward others. People may recall difficulties they have faced with certain products or services, making them more inclined to assist others experiencing similar issues.
- Sharing-feedback behaviour. This level of engagement involves more socially oriented behaviours, such as sharing information, knowledge and experiences with others. These behaviours can also include providing feedback to providers on existing solutions, suggesting new ones, co-developing products and services and urging policymakers to adjust their approaches.
- Recommend to others behaviour. Recommending behaviour, such as influencing or advocating, reflects active engagement. It occurs when individuals share their knowledge or experiences, often through word of mouth, to shape perceptions or preferences about certain products or services. This shift decentralizes decision-making and empowers households and communities, requiring a more human-centred approach from policymakers. While this creates opportunities for greater participation and empowerment of citizens, it also poses challenges in ensuring equitable involvement and managing the influence of personal recommendations.

Value creation is the major motivational driver of citizen engagement. Citizens are engaged when they have an opportunity to add value to the hydrogen transformation. Across the value dimension, the drivers of citizen engagement are as follows:

- Utilitarian value is derived from citizens' perception of potential financial benefits associated with the expected implementation of hydrogen technology.
- Social value refers to the benefits gained within social relationships, such as recognition from others for choosing sustainable solutions over conventional ones.
- Environmental value relates to the environmentally friendly features of hydrogen technology. It motivates citizens to prioritize collective interests over self-interest, emphasizing the broader benefits that hydrogen solutions can offer to the environment as a whole.

The value drivers of citizen engagement originate from the value added by hydrogen technology. Moreover, citizens can affect the value of hydrogen valleys through their feedback [40].

Hydrogen valleys are mainly perceived by citizens as a potential solution for reducing carbon emissions. Therefore, to enhance social acceptance, it is crucial to increase the public knowledge and understanding of hydrogen as a green energy technology [41].

A typical citizen-engagement strategy involves steps to identify and understand relevant stakeholders, define the scope and types of engagement activities, determine feasible engagement levels and establish a timeframe. To effectively facilitate citizen engagement, subsequent activities should be tailored to the specific project. Best practices include involving citizens in regular assessments of social acceptance, providing feedback and participating in the co-creation and testing of innovative hydrogen tools [30,32].

The range of hydrogen citizen-engagement tools for activation of the feedback mechanisms and inspiration of citizen collaboration are provided in Appendix A.

3.2. Data and Methodology

To assess the current state of citizen engagement with hydrogen technology in Cyprus and to propose effective engagement strategies, this study addresses the following research questions, focusing on the attitudes, views and opinions of various demographic groups (e.g., age, gender, education and employment status) in Cyprus:

- **Past Participation in Sustainability Programs**: Which demographic groups in Cyprus have previously participated in community or government programs dedicated to environmental sustainability? Understanding participation patterns will help identify groups that are more likely to engage in hydrogen-related initiatives and those who may need additional outreach or education.
- **Standpoint on Renewable Energy Transition**: What are the opinions of different demographic groups on transitioning to renewable energy sources in Cyprus? This question seeks to capture attitudes toward energy transformation, identifying both supporters and potential sceptics within the population, and assessing how these views vary across demographics.
- **Awareness of Hydrogen Economy**: What is the level of awareness among citizens regarding the potential benefits of a hydrogen economy for Cyprus? This question aims to gauge the current knowledge base on hydrogen's economic, environmental and societal advantages, thereby identifying areas for informational campaigns.
- **Interest in Hydrogen Transformation**: How is the interest in hydrogen transformation distributed among different demographic groups? This question explores which groups are most curious about hydrogen advancements, helping to target future engagement efforts effectively.
- **Information Sources on Energy and Environment**: What sources do different demographic groups in Cyprus use to obtain information on energy and environmental issues? Understanding these information channels can guide the design of communication strategies tailored to the media preferences of each demographic, ensuring that hydrogen-related information reaches its intended audience effectively.

Therefore, in the present study, we followed a quantitative research methodology operationalized by a survey instrument. The target audience was defined as the population of Cyprus above 18 years old. The survey was anonymous, and participation in the survey was entirely voluntary. All participants consent to taking the survey, and they could terminate their participation at any time without negative consequences. Additionally, participants were made aware that their responses would be used solely for research purposes.

The questionnaire was divided into four parts. In the first part, the citizens were informed about the context of the study and asked to provide demographic characteristics. In the second part of the questionnaire, citizens were asked to respond to a set of questions about their attitude to green energy transition in Cyprus and hydrogen awareness. The third part focused on specific questions, which collectively allowed us to assess respondents' current knowledge of the hydrogen economy. Finally, the fourth part collected data about potential engagement and participation in activities related to the creation of a hydrogen valley in Cyprus.

The questionnaire was purposefully developed through several brainstorming sessions by the authors in consultation with matter experts and later assessed and adjusted through two preliminary testing rounds. We used triangulation to validate our findings on hydrogen awareness via a subject-matter-expert interview, data from self-reported assessments by citizens and the 'hydrogen knowledge score' (see further explanations on this later in the paper). The questions were prepared in Greek and English languages. The participants were able to choose the language of the questionnaire at their discretion. The survey

included closed questions, 5-point Likert scale questions and open-ended questions to collect opinions and proposals about the hydrogen and renewable energy transformation in Cyprus. The questionnaire was made available to the citizens of Cyprus through local communication channels in digital form. The survey was conducted during the spring and summer of 2024. The collected data were analysed using StataNow/MP 18.5 for Windows.

Table 1 provides an overview of the demographic characteristics of the 378 survey respondents. The age distribution indicates that the majority (55.56%) were between 41 and 65 years old, representing citizens considered highly productive and active influencers. Another significant portion, 39.68%, fell within the 18–40 age group, often associated with future growth potential and innovation for the country. A smaller percentage, 4.76%, were aged 65 and above, reflecting the demographic group in retirement. Gender distribution was nearly even, with 50.79% male and 49.21% female respondents.

Table 1. Descriptive statistics of the respondents' profiles.

Demographics	ID	Category	Frequency	Percentage
Age group (years)	AGE	18–29	65	17.2
		30–39	85	22.48
		40–65	210	55.56
		65+	18	4.76
		Total	378	100
Gender	GEN	Male	192	50.79
		Female	186	49.21
		Total	378	100
Highest education level	EDU	Up to Secondary school	91	24.07
		Bachelor's degree	111	29.37
		Master's degree and above	176	46.56
		Total	378	100
Employment	EMP	Full-time	289	76.46
		Part-time	24	6.35
		Other	65	17.2
		Total	378	100
Sector of employment	SEC	Sectors with many H_2 applications *	65	17.2
		Others	313	82.8
		Total	378	100
Nationality	NAT	Cypriot	332	87.83
		Other	46	12.17
		Total	378	100
Residence in Cyprus	RES	Less than 10 years	29	7.67
		More than 10 years	349	92.33
		Total	378	100

* Energy, transport, industry and construction.

Regarding educational attainment, 46.56% held a master's degree or higher, 29.37% had a bachelor's degree and 24.07% had completed secondary education. Employment status indicates that most respondents (76.46%) worked full-time, while 6.35% were part-time employees and 17.20% fell into the "Other" category (pensioners, students, housekeepers, etc.).

In terms of employment sectors, 17.2% of respondents worked in sectors with significant hydrogen (H_2) applications, including energy, transport, industry and construction, while the remaining 82.8% were employed in other sectors. The sample predominantly consisted of Cypriots (87.83%), with 12.17% identifying as non-Cypriots. Most respondents

(92.33%) had lived in Cyprus for more than 10 years, while 7.67% had lived there for less than 10 years.

To address the research questions, we conducted a three-step approach to statistical analysis, particularly suited to the predominantly categorical nature of the data. First, we performed a descriptive analysis to summarize the key characteristics of the variables.

Next, we proceeded with hypothesis-testing to examine potential associations between our question of interest and the categorical variables. Using Fisher's exact test, we assessed whether the distribution of responses to a specific question varied across categories of demographic characteristics. Fisher's exact test, as an exact test of association, does not indicate direction or effect size; it merely determines if an association exists. A significant result leads to the rejection of the null hypothesis (H_0), indicating that the variables are not independent and suggesting the presence of an association.

In the final step, we estimated an ordered logit model to further explore the relationship, using an ordinal dependent variable in conjunction with independent categorical variables. Ordered logit models are used to estimate relationships between an ordinal dependent variable and a set of independent variables. An ordinal variable is a variable that is categorical and ordered, for instance, "Strongly oppose", "Somewhat oppose", "Neutral", "Somewhat support" or "Strongly support", which might indicate a person's standpoint on green transition. This model is perfectly suited to our empirical analysis, as we aim to explore how different categories of demographic groups respond to our ordered categorical dependent variable of interest. In this model, an underlying score is estimated as a linear function of the independent variables and a set of cutpoints. The probability of observing outcome *i* corresponds to the probability that the estimated linear function, plus random error, is within the range of the cutpoints estimated for the outcome.

The ordered logit model that we estimate has the following form:

$$\Pr(outcome_j = i) = \Pr\left(\kappa_{i-1} < \beta_1 X_{1j} + \beta_2 X_{2j} + \ldots + \beta_k X_{kj} + u_j \leq \kappa_i\right) \quad (1)$$

where u_j is assumed to be logistically distributed in the ordered logit. Depending on the question of interest, the outcome changes. In either case, we estimate the coefficients β_1, β_2, …,β_k of our independent variables (AGE, GEN, EDU, EMP, SEC, NAT, RES) and the variable knowledge score, together with the cut points κ_1, κ_2, …, $\kappa_{(k-1)}$, where k is the number of possible outcomes (κ_0 is taken as $-\infty$, and κ_k is taken as $+\infty$). j is the category of our ordered outcome. The knowledge score variable was organized as follows.

The survey contained twelve true-or-false statements related to hydrogen. The respondents were requested to choose one out of three answers: "I was aware of this/true"; "I did not know that/not sure it is true"; "It is false". Each correct answer increased the knowledge score by 2 points, the non-confident answer increased the score by 1 point, and each wrong answer changed the score by 0 points. Thus, the lowest score indicates that the respondent is less likely to know, while the highest score indicates better knowledge. The potential maximum hydrogen knowledge score was 24 points (all answers are correct), and the potential minimum score was 0 points (all answers are wrong). Descriptive statistics of the hydrogen knowledge score are provided in Appendix C.

Outcome is defined as any possible answer that the respondent can give [42] (see Long and Freese (2014, chap. 7) for a discussion of models for ordinal outcomes). For example, in 5-point Likert scale questions, the number of possible outcomes is 5. The coefficients and cutpoints were estimated using maximum likelihood. In our estimations, we did not have a constant, because the effect was absorbed into the cutpoints.

The estimation began by tabulating the dependent variable. Category $i = 1$ is defined as the minimum value of the variable, $i = 2$ as the next ordered value, and so on, for the

empirically determined k categories. The probability of a given observation for ordered logit is given by:

$$\begin{aligned} p_{ij} &= \Pr(y_j = i) = \Pr(\kappa_{i-1} < X_j\beta + u \leq \kappa_i) \\ &= \frac{1}{1+\exp(-\kappa_i + X_j\beta)} - \frac{1}{1+\exp(-\kappa_{i-1} + X_j\beta)} \end{aligned} \quad (2)$$

To interpret the impact of a categorical independent variable (e.g., gender) on the probability of different outcomes of the ordered dependent variable, we estimated average marginal effects. Particularly, we estimated how the predicted probabilities changed when a demographic variable such as gender changes from 0 (male) to 1 (female), while holding other variables constant. Our results provide the average predicted probabilities for each category (possible outcome) of our dependent variable for males and females.

This model allowed us to confirm our initial findings and to predict classification probabilities across the different categories, thus providing a more detailed understanding of the associations identified.

4. Results

In this subsection, we present the results of our descriptive analysis, along with the average predicted probabilities derived from the estimation of an ordered logit model, which is well suited for analysing the qualitative data in our study.

Past Participation in Sustainability Programs. As regards the first research question—which demographic groups in Cyprus have previously participated in community or government programs dedicated to environmental sustainability?—the descriptive statistics show that 14.8% of respondents had such experience. Figure A1 in Appendix B presents pie charts depicting the distribution of respondents across various demographic groups who reported participation in such programs. The descriptive statistics reveal that the individuals most likely to have such experience are aged between 40 and 65 (42.86%), female (55.36%), highly educated (53.57%), employed in non-related sectors (64.29%) and Cypriots (85.71%). The pie charts presented in Figure A1 in Appendix B show that those employed in non-related sectors and Cypriots are more active in participating in such kinds of programs, but the results from our ordered logit estimation reveal the opposite. Before proceeding with the estimation of the ordered logit model, we formulated and tested seven corresponding null hypotheses for those seven demographic groups.

For seven demographic factors (age group, gender, education level, employment status, sector of employment, nationality and residence in Cyprus), we formulated and tested seven corresponding null hypotheses:

H_0: A1–A7. *There is no association between participation in environmental programs and the respective demographic factor.*

Based on the p-values from Fisher's exact test for association, presented in Table A1 in Appendix B, an association was identified—resulting in the rejection of the null hypothesis—for only three demographic factors: age group (at 5% significance level), sector of employment (at 1% significance level) and residence in Cyprus (at 5% significance level). Small p-values indicate that the participation in environmental programs varies across respondents, and the difference is strongly statistically significant for those who are employed in a related sector with those who are not employed in the related sector. Moreover, participation in environmental programs differs across different age groups. Finally, those who have lived more than 10 years in Cyprus reply differently from those who live in Cyprus for less than 10 years, and this difference is statistically significant.

Through the application of the logit model, we quantified the effect of these demographic factors on participation in community or government programs dedicated to environmental sustainability. The fractions of citizens with or without experience of

participation in environmental programs for each demographic group are presented in Table 2.

Table 2. Fractions of citizens participated in environmental programs by demographic groups.

Demographic Factor	Category	Yes	No
Age Group	18–29	0.23	0.77
	30–39	0.14	0.86
	40–65	0.12	0.88
	65+	0.13	0.87
Sector of employment	With many H_2 applications	0.27	0.73
	Others	0.12	0.88
Residence in Cyprus	Less 10 years	0.26	0.74
	More 10 years	0.14	0.86

From Table 2 and Figure 2, we observe the following trends with respect to the past participation in environmental programs:

- Younger individuals, especially those in the 18–29 age group, show higher participation rates (23%) in environmental programs compared to older age groups.
- People working in sectors related to hydrogen (H_2) are more likely to participate (27%). This may suggest that individuals having a better understanding of environmental issues are more willing to support sustainability initiatives.
- Those who have lived in Cyprus for less than 10 years are more active in participating (26%).

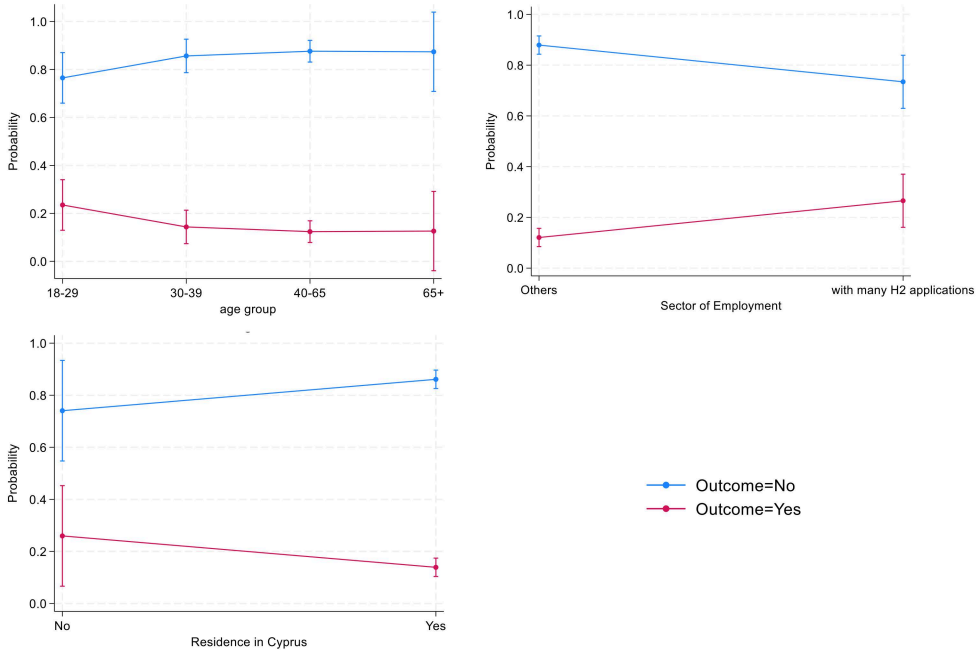


Figure 2. Predictive margins of demographic groups participated in environmental programs with a 95% confidence interval.

Descriptive statistics serve as an essential starting point but fall short in capturing the complex relationships inherent in ordered outcomes. For example, the initial descriptive analysis does not account for the simultaneous influence of multiple variables or the ordered nature of the dependent variable. Unlike descriptive statistics, the ordered logit model captures the ordered structure of the dependent variable and accounts for covariate effects. The model that we estimate provides a more robust and representative analysis that is both statistically and practically meaningful.

Standpoint on Renewable Energy Transition. The second research question—what are the opinions of different demographic groups on transitioning to renewable energy sources in Cyprus?—aims to provide insights into the current views of citizens in Cyprus on the green economy transition.

The descriptive statistics suggest a broad consensus among respondents in favour of renewable energy in Cyprus, with 89.95% expressing supportive views. Notably, more than half the respondents (57.41%) strongly supported the transition, indicating firm backing for a green economy in Cyprus. Meanwhile, 9.52% of respondents were neutral, and 0.53% strongly opposed to the transition. Figure A2 in Appendix B shows the corresponding pie chart for the whole population, while Figure A3 shows seven different pie charts for each demographic group.

In a similar way to the previous research question, the following seven null hypotheses for the various demographic factors were examined:

H_0:B1–B7. *There is no association between the standpoint on renewable energy transition and the respective demographic factor.*

The results of the hypothesis testing, shown in Table A1 in Appendix B, indicate that three demographic factors—age group, education level and employment status—are statistically significant at the 5% significance level (age group) and 1% significance level (education and employment status). This suggests that these factors are meaningfully associated with individuals' standpoints on the renewable energy transition in Cyprus. For the remaining demographic factors, we failed to reject the null hypothesis, meaning there is not enough evidence to conclude an association between these factors and citizens' standpoints on renewable energy.

To validate the insights gathered from the descriptive statistics, we extended our analysis by applying an ordered logit model. This approach allows us to examine how demographic factors influence respondents' levels of support for the renewable energy transition in a more detailed way. The distribution of respondents' views, categorized by levels of support, is presented as fractions derived from the ordered logit regression in Table 3.

Table 3. Citizens' opinions on renewable energy transition by demographic groups.

Demographic Factor	Category	Strongly Oppose	Neutral	Somewhat Support	Strongly Support
Age Group	18–29	0.01	0.15	0.40	0.44
	30–39	0.00	0.06	0.25	0.69
	40–65	0.01	0.10	0.34	0.56
	65+	0.00	0.07	0.27	0.66
Highest education level	Up to Secondary school	0.01	0.11	0.36	0.52
	Bachelor's degree	0.01	0.12	0.38	0.49
	Master's degree and above	0.00	0.07	0.27	0.65
Employment	Full-time	0.00	0.09	0.31	0.60
	Part-time	0.01	0.17	0.41	0.41
	Other	0.01	0.11	0.36	0.53

From Figure 3 and the data in Table 3, which provide a breakdown of citizens' opinions across levels of support on renewable energy transition, we observe the following trends:

- Respondents in the age group 30–39 show the highest strong support (69%) among age groups, suggesting middle-aged individuals may be more enthusiastic about renewable energy and more concerned about the long-term sustainable development of the country.

- The data evidence that support for renewable energy increases with education level. Respondents with a master's degree or above show the highest level of strong support (65%).
- Respondents in full-time employment show the highest level of strong support (60%). This suggests that they may feel more socially defended and with longer plans for stable development.

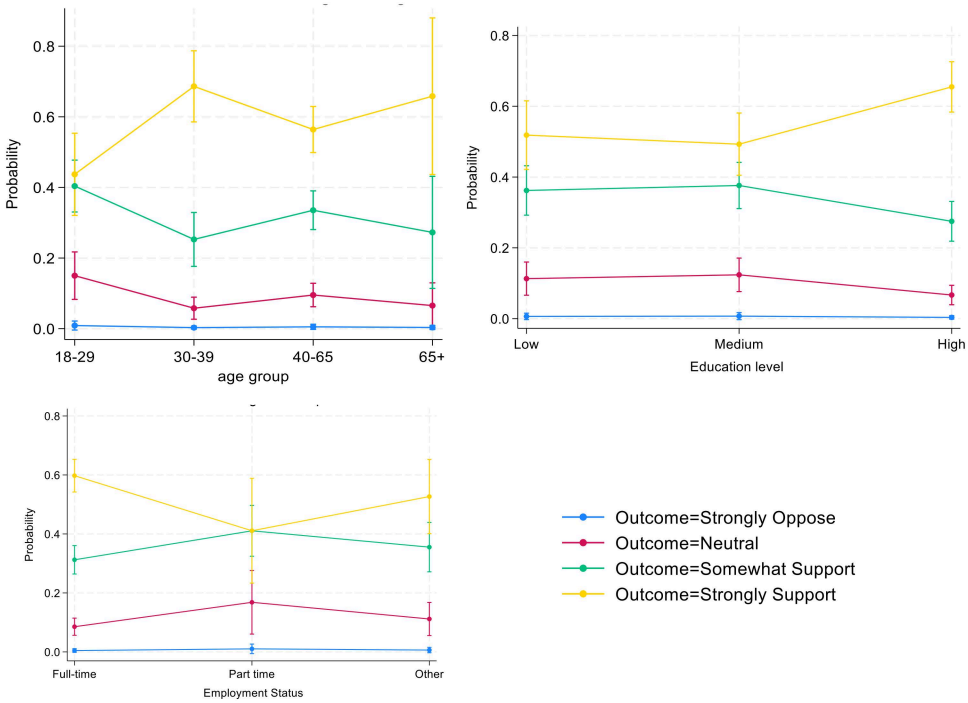


Figure 3. Predictive margins of demographic groups regarding their standpoint on renewable energy transition with a 95% confidence interval.

In sum, the largest support for renewable energy transition comes from middle-aged, more educated and fully employed individuals.

Awareness of Hydrogen Economy. Our survey was purposefully built and included some pioneering elements, not found, to the best of our knowledge, in research by others. In particular, our research question on hydrogen awareness was approached from two perspectives. Respondents were first asked to answer two self-assessment questions about their familiarity with the hydrogen economy overall and their awareness of the specific benefits of introducing hydrogen in Cyprus. This helped capture respondents' subjective perceptions of their knowledge of the topic. The survey then included twelve true-or-false statements related to hydrogen, which respondents were required to evaluate. These statements served as a test of respondents' actual knowledge, allowing for a more objective assessment by constructing a cumulative "hydrogen knowledge score" variable. This is our pioneering approach, which, to our knowledge, has not been implemented in any other hydrogen awareness surveys.

We continued the analysis by setting two null hypotheses:

H_0:C1. *There is no association between awareness of a hydrogen economy and the hydrogen knowledge score.*

H_0:C2. *There is no association between awareness of the specific benefits of introducing hydrogen in Cyprus and the hydrogen knowledge score.*

Both hypotheses were rejected by the application of Spearman's rank correlation coefficients. For both cases, the correlation coefficients are equal to 0.43, while the *p*-values for these hypotheses are 0, indicating that we strongly reject the null hypothesis that those two variables are independent.

Descriptive statistics in Figure A4 in Appendix B reveal that 61.90% of respondents were unfamiliar with the concept of a hydrogen economy, while 33.07% reported being somewhat familiar, and only 5.03% considered themselves very familiar. Regarding the awareness of the potential benefits of a hydrogen economy specifically for Cyprus, 53.97% of respondents indicated that they are unaware of these advantages, 21.96% were uncertain and 24.07% believed they were well informed. These results are presented in Figure A5 in Appendix B.

In the next step of the analysis, the following seven null hypotheses for the various demographic factors were examined:

H_0:C3–C9. *There is no association between awareness of the hydrogen economy and the respective demographic factor.*

Based on the results of *p*-values for Fisher's exact test for association, shown in Table A1 in Appendix B, we defined that six demographic factors were statistically significant. These demographic factors were age and gender—significant at 10% significance level; and education level, sector of employment, nationality and years of residence in Cyprus—significant at 1% significance level.

Table 4, which is based on an analysis of the ordered logistic model, provides a breakdown of citizens' familiarity with the hydrogen economy across various demographic groups and highlights specific groups with lower awareness, suggesting that targeted educational efforts could be beneficial in raising awareness about the hydrogen economy across the population.

Table 4. Citizens' self-assessment of hydrogen economy awareness.

Demographic Factor	Category	Not Familiar at All	Somewhat Familiar	Very Familiar
Age Group	18–29	0.61	0.34	0.05
	30–39	0.64	0.32	0.05
	40–65	0.62	0.33	0.05
	65+	0.50	0.42	0.08
Gender	Male	0.58	0.36	0.06
	Female	0.65	0.31	0.04
Highest education level	Up to Secondary school	0.73	0.24	0.03
	Bachelor's degree	0.65	0.31	0.04
	Master's degree and above	0.53	0.40	0.07
Sector of employment	With many H_2 applications	0.40	0.49	0.11
	Others	0.66	0.30	0.04
Nationality	Cypriot	0.63	0.33	0.04
	Other	0.49	0.43	0.08
Residence in Cyprus	Less 10 years	0.35	0.52	0.13
	More 10 years	0.63	0.32	0.04

The main findings from Table 4 and Figure 4 can be summarized as follows:

- The middle-aged respondents (30–39) reported the greatest unfamiliarity, with 64% not familiar at all.
- Females reported a higher rate of unfamiliarity (65% not familiar) compared to males (58%).
- Respondents with a lower level of education showed the least familiarity, with 73% indicating they were not familiar at all. Familiarity improved slightly among those

with higher education levels, with 7% of those holding a master's degree or higher considering themselves very familiar.

- Respondents in other sectors showed less familiarity, with 66% not familiar at all. In contrast, those working in fields with many hydrogen applications reported higher familiarity levels, with 11% being very familiar.
- Cypriots showed slightly more unfamiliarity (63% not familiar) compared to others (49%). However, the "very familiar" percentages are comparable for both groups.
- Those who had resided in Cyprus for more than 10 years were more unfamiliar (63% not familiar) than those who had lived there for less than 10 years (35% not familiar), although recent residents reported a higher "somewhat familiar" rate at 52%.

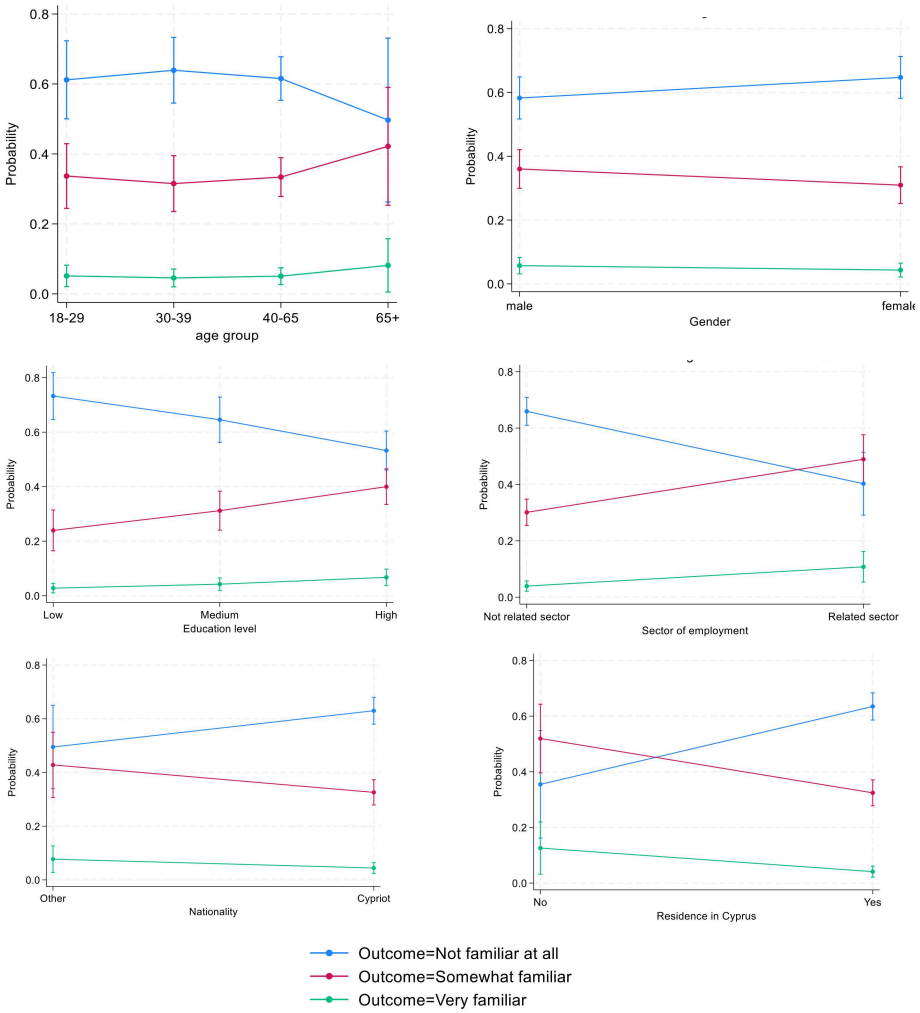


Figure 4. Predictive margins of demographic groups for their self-assessment of hydrogen economy awareness with a 95% confidence interval.

Interest in Hydrogen Transformation. To have insights for engagement strategy design, the respondents were requested to express their willingness to join in some discussions or other activities related to the creation of a hydrogen valley in Cyprus.

From the descriptive statistics shown in Figure A6 in Appendix B, we see that 51.85% of respondents were "somewhat likely", 27.25% were "very likely" and only 20.90% of respondents answered that they were "not likely" to join in discussions or activities related to the creation of a hydrogen valley in Cyprus.

To examine further, we studied whether their answer depended on their demographic characteristics. The following seven null hypotheses for the various demographic factors were examined:

H_0:D1–D7. *There is no association between willingness to participate in the creation of a hydrogen valley in Cyprus and the respective demographic factor.*

Based on the exact Fisher's test, the answer of respondents to this question was associated with gender (at 5% significance level) and with the employment sector of the respondents (at 1% significance level), as presented in Table A1 in Appendix B. This indicates that the answer of respondents mainly varied based on their gender and employment sector, and the rest of their characteristics, such as age or education, did not influence their answers.

Table 5 and Figure 5 provide the results of the ordered logit model. The table illustrates citizens' likelihood of participating in the creation of a hydrogen valley in Cyprus, segmented by gender and sector of employment.

Table 5. Citizens' interest in participating in the creation of a hydrogen valley in Cyprus.

Demographic Factor	Category	Not Likely	Somewhat Likely	Very Likely
Gender	Male	0.17	0.51	0.32
	Female	0.25	0.53	0.23
Sector of employment	With many H_2 applications	0.13	0.48	0.39
	Others	0.22	0.53	0.25

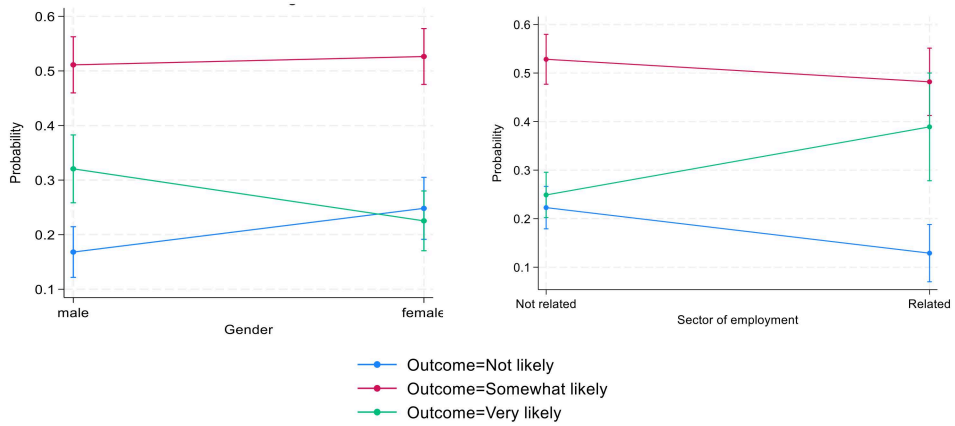


Figure 5. Predictive margins of demographic groups regarding their interest in participating in the creation of a hydrogen valley in Cyprus with a 95% confidence interval.

The main trends concerning potential involvement in the creation of a hydrogen valley in Cyprus are as follows:

- Males were more likely to participate, with 32% indicating they were very likely, compared to 23% of females. Additionally, fewer males (17%) were not likely to participate, while 25% of females fell into this category.
- Those employed in sectors with many hydrogen applications showed the highest likelihood of participation, with 39% being very likely and only 13% not likely to participate.

Information Sources on Energy and Environment: Respondents were asked to indicate the sources they use to obtain information about energy and environmental issues. Several options were provided, including "Through the Internet and/or social media",

"Through books and/or printed press", "Through work", "Through studies/degree" and "Others". The respondents could select multiple options.

The most commonly selected source was "Through the Internet and/or social media", accounting for 65.28% of the total choices. This was followed by "Through books and/or printed press" (14.19%) and "Through work" (11.35%); see Figure A7 in Appendix B.

In Figure A8, in Appendix B, we see that a strong majority of respondents (71.62%) gave positive responses to the question, "Are you interested in learning about hydrogen in the energy transition?". In contrast, only 8.22% indicated a lack of interest. Additionally, 20.16% of respondents were undecided, representing a group that should be targeted by engagement strategies.

The following seven null hypotheses on the associations of various demographic factors were examined:

H_0:E1–E7. *There is no association between interest in knowing about hydrogen and the respective demographic factor.*

Based on the results of *p*-values for Fisher's exact test for association, shown in Table A1 in Appendix B, the following demographic factors were defined as significant: gender at 5% significance level and sector of employment at 10% significance level.

The results of the ordered logit regression for these demographic factors are presented in Table 6 and Figure 6.

Table 6. Citizens' interest in knowing about hydrogen.

Demographic Factor	Category	Not Likely	Somewhat Likely	Very Likely
Gender	Male	0.08	0.19	0.73
	Female	0.09	0.21	0.70
Sector of employment	With many H_2 applications	0.06	0.15	0.79
	Others	0.09	0.21	0.70

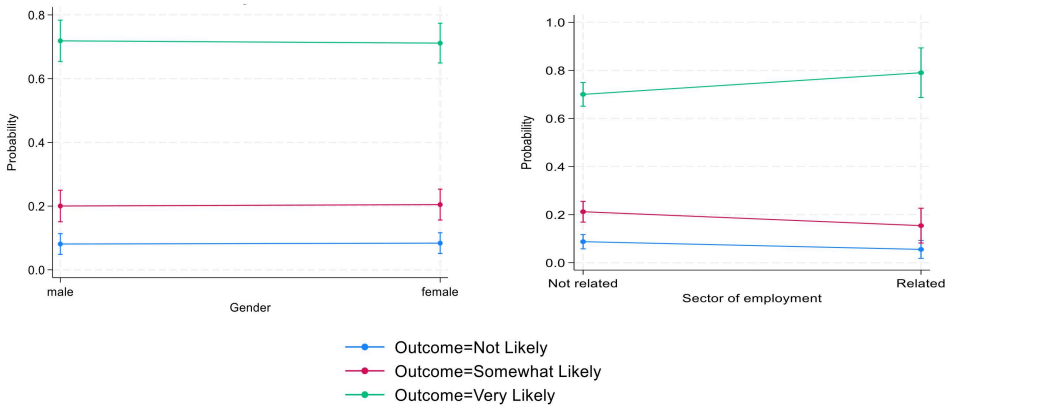


Figure 6. Predictive margins of demographic groups regarding their interest in knowing about hydrogen with a 95% confidence interval.

The main findings regarding citizens' interest in knowing about hydrogen can be summarized as follows:

- Male respondents exhibited slightly higher interest levels in the "Very Likely" category.
- Individuals employed in sectors with many hydrogen applications showed the highest likelihood of interest in learning about hydrogen (79% "Very Likely").

The results of the survey data analysis offer valuable insights into citizen engagement regarding the development of a hydrogen valley in Cyprus. These findings shed light on

the public's interest, awareness and potential involvement in this innovative project, highlighting key demographic factors that influence their engagement levels. By understanding these insights, policymakers and stakeholders can tailor their strategies to effectively involve citizens, foster collaboration and promote the adoption of hydrogen technologies within the region.

5. Discussion

The results of the hydrogen-related survey conducted among Cypriot citizens indicate a generally positive public perception of hydrogen technology as a pivotal component of the energy transition. The findings show that citizen willingness to engage in discussions or activities related to the creation of a hydrogen valley in Cyprus was distributed as follows: 25% of citizens were very likely to participate; 55% were somewhat likely to participate; and 20% were unlikely to participate. With respect to the green energy transition, approximately 60% of citizens across various demographic groups strongly endorsed the green energy transition, while about 30% were somewhat supportive, and only 10% were neutral or negative.

The survey further highlights a substantial willingness to participate in future actions related to the creation of a hydrogen valley in Cyprus. Specifically, about 30% of respondents were very likely to participate, around 50% were somewhat likely and 20% were unlikely to contribute.

Figure 7 summarizes the statistically significant associations between demographic factors and various aspects of citizen engagement with hydrogen in Cyprus. The results indicate that age (AGE), gender (GEN) and sector of employment (SEC) show the highest number of associations (three to four each), while education (EDU) and residence in Cyprus (RES) have two associations each. In contrast, employment status (EMP) and nationality (NAT) are associated with only one aspect each.

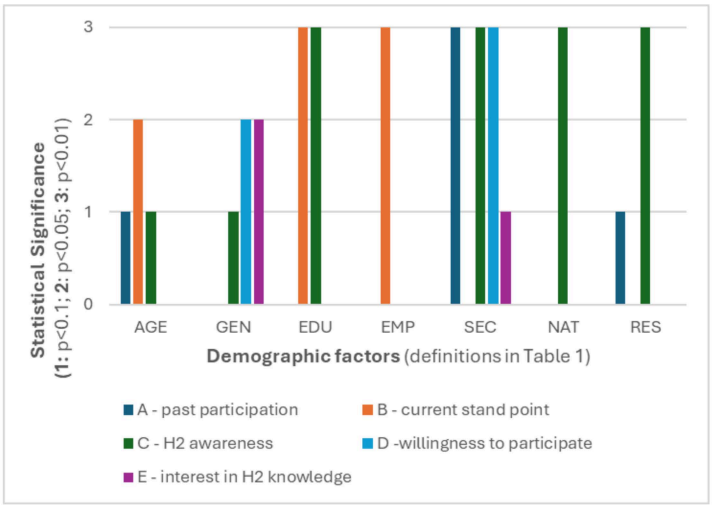


Figure 7. Associations of demographic factors with hydrogen engagement.

However, citizen engagement remains a critical prerequisite for establishing a hydrogen valley in Cyprus and requires ongoing attention. The questionnaire design allows temporal analysis, examining past experience, current standpoints and readiness for future actions. In Table 7, the survey results are aligned with the framework for the development of citizen engagement over time, as illustrated in Figure 1.

Table 7. Citizens' attitude to a hydrogen valley in Cyprus.

Indicator	Past participation in sustainability programs	Current standpoint on green energy transition	Future involvement with a hydrogen valley
Active Demographic Group	Young individuals, employed in sectors with many H_2 applications, recent Cyprus residents	Middle-aged, educated, fully employed individuals	Male individuals, employed in sectors with many H_2 applications

Most of the population had reached the "Engagement decision" stage and had decided positively regarding hydrogen in Cyprus. However, survey data highlight that, among the three forms of engagement ("Advocacy", "Action" and "Awareness"), citizens of Cyprus are primarily engaged in the weakest form, "Awareness", with the predominant behaviour being "Seeking information".

One of the open-ended questions in the survey invited respondents to submit questions regarding hydrogen technologies or the hydrogen economy about which they would like more information. Many questions focused on the following:

- **What hydrogen technology and hydrogen economy are**—People want to know the basics of hydrogen as an energy source and how it functions within an economy.
- **Safety and environmental impact**—Concerns about how safe hydrogen technology is for use in households, vehicles and energy production.
- **Cost and economic impact**—Questions about the cost of hydrogen production, its affordability and whether it is economically advantageous compared to other renewable energy sources.
- **Practical applications**—Inquiries into how hydrogen can be applied in Cyprus, for households, vehicles or broader industries.
- **Benefits over other technologies**—Curiosity about the advantages of hydrogen over other renewable energy sources and traditional fuels.
- **Government support and subsidies**—Interest in knowing if there will be financial support from the government or the EU to encourage the use of hydrogen technology in Cyprus.

These insights suggest that hydrogen engagement strategies in Cyprus should focus on population segments with limited awareness of hydrogen technology—particularly middle-aged individuals, women, those with lower education levels and long-term residents (over 10 years). Efforts should aim to provide sufficient information about hydrogen to enable these groups to make informed decisions, either positively or negatively, regarding their engagement.

Additionally, tailored strategies should also target demographic groups of active supporters (as outlined in Table 7) to elevate them to higher forms of engagement. The motivational drivers for their engagement could include the utilitarian, social and environmental value added by hydrogen technology, as well as the value added by their active participation in hydrogen-related initiatives.

According to public opinion, the main potential challenges to introducing a hydrogen valley in Cyprus can be categorized into three groups, along with the percentage of total responses:

- **Frequently mentioned challenges (20%)**: Public concerns about the safety of hydrogen and lack of industrial infrastructure.
- **Occasionally mentioned challenges (14%)**: Lack of general acceptance and awareness, lack of expertise and human resources and insufficient knowledge to judge.
- **Infrequently mentioned challenges (11%)**: The high cost of the technology and availability of funding.

These responses highlight that safety concerns, infrastructure gaps and financial limitations, as well as a general need for increased awareness, expertise and public acceptance of hydrogen technologies in Cyprus should be addressed by engagement strategies.

In addition, respondents were directly invited to provide suggestions for citizen engagement in the hydrogen valley pilot in Cyprus. The suggestions for designing citizen engagement strategies, provided in response to this open-ended question, can be grouped as follows:

- **Information and Education**: A significant portion of the responses emphasized the need for more public information and education. This includes informing citizens about the benefits and potential of hydrogen energy, especially regarding its role in the green economy, and dispelling any uncertainties about its safety and application.
- **Incentives for Participation**: Many respondents believe that citizens need incentives to engage with the project. These could include reduced energy costs or other economic benefits, such as job opportunities or housing-related perks.
- **Pilot Projects and Demonstrations**: Several responses suggest starting with pilot programs or trials in local communities. This would give citizens a tangible demonstration of the potential benefits and allow them to assess the project first-hand before committing further. The results of these pilot projects should then be shared with the public.
- **Workforce Development**: Some respondents highlighted the importance of creating new job opportunities, especially for young people and professionals in fields related to hydrogen technology.
- **Public Consultations and Involvement**: There were calls for increased citizen involvement in the planning and execution stages, through consultation processes and participatory research. This would ensure that the community's needs and concerns are addressed in the development of the hydrogen valley.

Barriers to citizen engagement with hydrogen technology in Cyprus arise from social, economic, cultural and technical factors. A lack of public awareness and knowledge about hydrogen's benefits, coupled with perceived safety concerns, fosters scepticism and fear. These issues can be addressed through targeted public education campaigns, simplifying technical information and conducting safety demonstrations to build trust. Additionally, showcasing successful hydrogen projects and involving trusted community figures can help dispel misconceptions and promote confidence.

Economic barriers, such as the high costs of adopting hydrogen technologies and limited financial incentives, as well as infrastructure gaps, can be mitigated by introducing subsidies, tax benefits and financing options to make hydrogen more accessible. Investments in developing a robust hydrogen infrastructure, such as fuelling stations and production facilities, are essential to improve practicality. Addressing cultural resistance requires promoting the societal and environmental benefits of hydrogen while engaging citizens in decision-making to foster a sense of ownership. Rebuilding trust in government institutions through transparency and consistent communication, coupled with participatory approaches that include local communities, can enhance public support and drive the adoption of hydrogen technology.

To make the insights into the current status of citizen engagement in hydrogen technology in Cyprus, as revealed by the study, actionable, and to further effectively facilitate citizen engagement, appropriate engagement tools should be used. Appendix A provides sets of citizen engagement tools for fostering awareness and education, activating feedback mechanisms and inspiring citizens to collaborate.

Based on insights into the current status of citizen engagement in hydrogen technology in Cyprus, particularly taking into account that the internet and social media are the main sources of information, the following top 10 engagement tools are identified by authors as

the most appropriate for fostering citizens' awareness and education about hydrogen in Cyprus:

- Informational websites with educational content, news and project updates;
- Awareness campaigns on social network platforms;
- YouTube channels focused on hydrogen education and awareness;
- Virtual workshops where citizens learn about hydrogen and ask questions;
- Open days at hydrogen production plants, research labs or project sites;
- Demonstrations of showcases (e.g., fuel cells and hydrogen refuelling stations);
- Exhibitions at community events, science fairs or museums;
- Educational apps with interactive content (quizzes, videos and simulations) to engage younger citizens in particular;
- Environmental education centres as an integral part of the educational system;
- University programs, including distance-learning programs, to teach young citizens about hydrogen energy.

Regarding tailored engagement strategies for active supporters of hydrogen in Cyprus, the following Top 10 engagement tools have been identified by authors to elevate their involvement to the 'Action' and 'Advocacy' levels of engagement by activating feedback mechanisms and inspiring citizen collaboration:

- Discussions and interviews with small focus groups to gather in-depth feedback;
- Feedback forms integrated into specialized websites;
- Feedback sessions incorporated into workshops and seminars;
- Public forums to discuss concerns and engage with project representatives;
- Open innovation portals to propose ideas and refine concepts collectively;
- Citizen advisory committees to co-develop strategies and solutions;
- Community councils to ensure collaboration and shared decision-making;
- Awards for innovative hydrogen ideas and collaboration;
- Citizen portals to engage with project leaders and contribute ideas;
- Pilot programs to involve citizens in testing new hydrogen solutions.

To be effective, citizen engagement strategies should not be a one-time exercise. As shown in Figure 1, the development of citizen engagement is an ongoing process that evolves over time. Therefore, engagement strategies must be dynamic as well. The desired outcome of these strategies—transitioning citizens from being merely passive recipients to becoming co-creators, active participants and co-owners of hydrogen projects—can be achieved only through the continuous improvement of engagement strategies.

The ordered logit model assumes the proportional odds (or parallel lines) assumption. If this assumption is violated, then we would have to estimate the generalized ordered logit model. To ensure the robustness of the analysis, a sensitivity check was conducted using the Brant test. The null hypothesis of the Brant test is that the odds ratios are equal across the categories of the outcome variable, which means that the parallel odds assumption holds. Given that we failed to reject the null hypothesis, this indicates the selection of the estimating ordered logit model is appropriate and is confirmed by the results of the Brant test.

While this study provides valuable insights into public attitudes toward hydrogen energy in Cyprus, it also has some limitations that need to be further addressed in future research. First of all, the survey captures opinions at a specific moment, which may not reflect evolving attitudes as awareness of hydrogen technologies grows or policies change. Public attitudes toward hydrogen should be further assessed to ensure that citizen engagement is dynamically embedded in the decision-making mechanism. Second, the results may not be easily comparable to other countries due to Cyprus's unique socio-economic, political and

geographic conditions. In broad terms, strategies for citizen hydrogen engagement should include two components: one component related to the technology, which is common for various countries, and the second one is a country-specific component. Thus, future similar country-specific studies focusing on citizen engagement in the implementation of hydrogen technology would help to overcome this limitation and crystalize both components.

6. Conclusions

This study demonstrates a strong public inclination toward supporting the green energy transition in Cyprus, with approximately 80% of the population potentially willing to participate in the creation of a hydrogen valley in Cyprus. However, about 75% of the population across various demographic groups lacks full awareness of the advantages and risks of hydrogen technology and expresses a desire for more information about it. This study highlights that among the three "AAA" forms of engagement (advocacy, action, awareness), most of the population is engaged through the weakest form, "Awareness", with their primary behaviour being "seeking information".

In addition, to maximize the societal impact of hydrogen implementation, it is imperative that policymakers integrate technological deployment with coordinated and dynamic engagement frameworks. These frameworks must emphasize utilitarian, social and environmental value creation to build public trust and sustained participation. By addressing the interplay between technological adoption and citizen involvement, Cyprus can position itself as a model for achieving carbon neutrality through hydrogen technology.

For future research, the authors invite scholars to perform similar country-specific studies focusing on citizen engagement in the implementation of hydrogen technology in specific countries. Such academic contributions can help achieve carbon neutrality in Europe by 2050 and advance hydrogen technology, which is one of the key innovations for a successful clean energy transition in Europe.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

The range of hydrogen citizen engagement tools

Citizen hydrogen engagement tools applicable for fostering awareness and education include the following:

- *Public awareness campaigns* to raise hydrogen awareness;
- *Infographics* to explain how hydrogen works and its environmental benefits;

- *Virtual workshops* where citizens learn about hydrogen and ask questions;
- *E-learning platforms* to offer free or low-cost online courses about hydrogen;
- *Informational websites* with educational content, news and project updates;
- *Resource libraries* with downloadable guides, whitepapers, reports, etc.;
- *Demonstrations of showcases* (e.g., fuel cells and hydrogen refuelling stations);
- *Open days* at hydrogen production plants, research labs or project sites;
- *Educational apps* with interactive content (quizzes, videos and simulations);
- *Virtual reality* experiences to immerse citizens in hydrogen systems;
- *University programs* to teach young citizens about hydrogen energy;
- *Environmental education centres* as an integral part of the educational system;
- *Exhibitions* at community events, science fairs or museums;
- *Roadshows* to showcase hydrogen solutions;
- *Awareness campaigns* on social network platforms;
- *Interactive live sessions* to engage citizens in real-time discussions;
- *Seminars* to conduct educational events on hydrogen energy;
- *Collaborations with influencers* to spread awareness about hydrogen projects;
- *Printed brochures* distributed at community centres, schools and public places;
- *Newsletters* (digital or printed) with updates and case studies;
- *Educational films* on hydrogen technology: its uses, benefits and challenges;
- *YouTube channels and podcasts* focused on hydrogen education and awareness;
- *Public demonstrations* where citizens can see hydrogen technologies in action;
- *Interactive maps* to show the location of hydrogen projects;
- *Data visualization tools* that help citizens understand the progress.

The hydrogen engagement tools for activation of the feedback mechanisms include the following:

- *Online surveys* to collect structured feedback;
- *Interactive polls* to gauge opinions on specific questions;
- *Discussions and interviews* with small focus groups to gather in-depth feedback;
- *Public forums* to discuss concerns and engage with project representatives;
- *Suggestion boxes* to submit ideas and feedback anonymously;
- *Comment sections* on project websites and social media platforms;
- *Feedback kiosks* with touchscreen interfaces in public areas;
- *Mobile apps* to conduct surveys and engage with citizens on-the-go;
- *Feedback forms* integrated into specialized websites;
- *Idea management systems* to manage and prioritize citizen ideas and feedback;
- *Feedback sessions* incorporated into workshops and seminars.

The hydrogen engagement tools for inspiring citizen collaboration include the following:

- *Collaborative design* workshops to brainstorm ideas and solutions;
- *Hackathons* to develop innovative hydrogen solutions over a short period;
- *Crowdsourcing platforms* to submit, share and collaborate on ideas;
- *Open innovation portals* to propose ideas and refine concepts collectively;
- *Citizen advisory committees* to co-develop strategies and solutions;
- *Community councils* to ensure collaboration and shared decision-making;
- *Contests* where citizens collaborate on solutions for hydrogen adoption;
- *Awards* for innovative hydrogen ideas and collaboration;
- *Citizen portals* to engage with project leaders and contribute ideas;
- *Pilot programs* to involve citizens in testing new hydrogen solutions;
- *Citizen-led initiatives* to develop and implement hydrogen technologies;
- *Skill-building workshops* to work together on practical applications;

- *Collaborative learning events* to foster knowledge-sharing;
- *Webinars* that incorporate breakout rooms to collaborate on ideas;
- *Public–private partnerships* to work together on hydrogen implementation.

Appendix B

Table A1. *p*-Values for Fisher's exact test for association.

The Null Hypothesis	AGE	GEN	EDU	EMP	SEC	NAT	RES
H_0: A1–A7	0.069 *	0.385	0.538	0.269	0.000 ***	0.657	0.056 *
H_0: B1–B7	0.015 **	0.332	0.005 ***	0.009 ***	0.444	0.331	0.775
H_0: C3–C9	0.090 *	0.071 *	0.009 ***	0.832	0.000 ***	0.000 ***	0.000 ***
H_0: D1–D7	0.412	0.020 **	0.250	0.464	0.006 ***	0.798	0.119
H_0: E1–E7	0.320	0.038 **	0.105	0.188	0.100 *	0.752	0.204

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

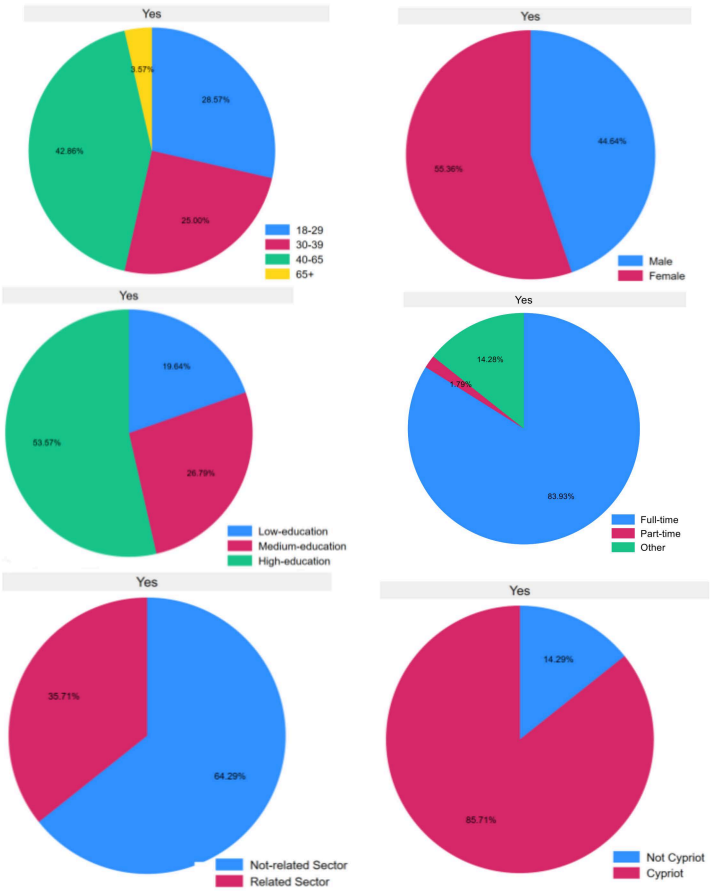


Figure A1. *Cont.*

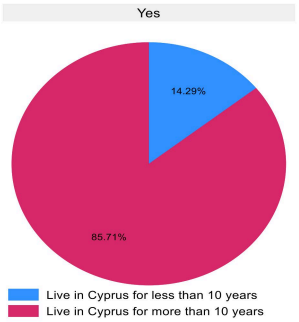


Figure A1. Pie charts by demographic categories for those who answered that they had been a part of any community or governmental program dedicated to environmental sustainability.

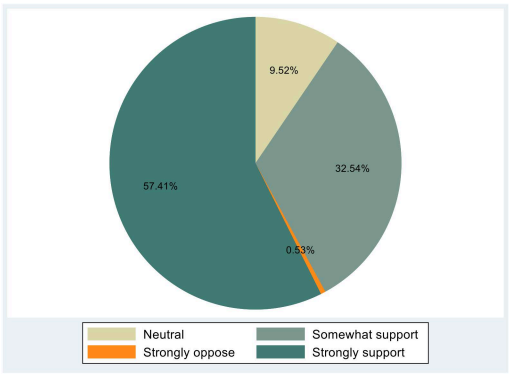


Figure A2. What is your standpoint on the transition to renewable energy sources in Cyprus? (Total).



Figure A3. *Cont.*



Figure A3. *Cont.*

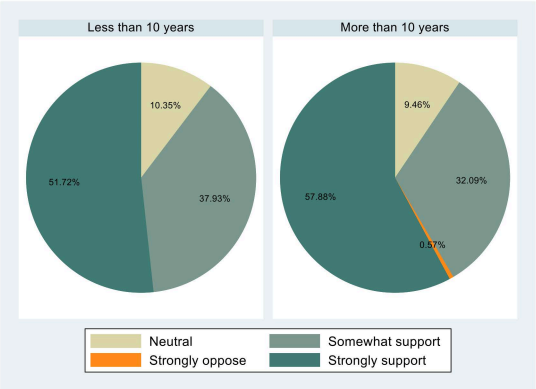


Figure A3. What is your standpoint on the transition to renewable energy sources in Cyprus? (By demographic group).

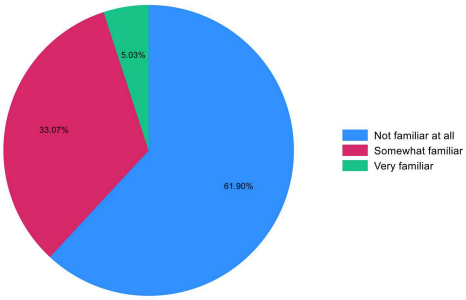


Figure A4. Do you know what a hydrogen economy is?

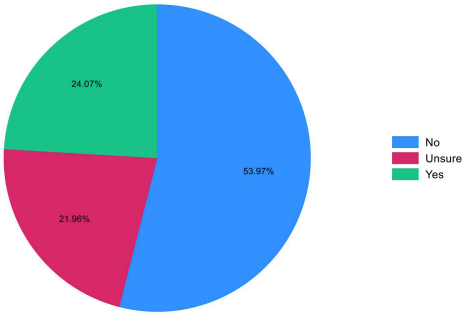


Figure A5. Are you aware of the prospective advantages of a hydrogen economy for Cyprus?

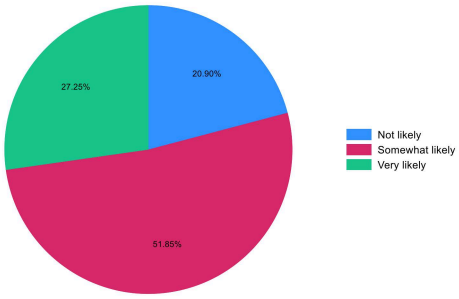


Figure A6. How willing would you be to join in some discussions or activities related to the creation of a hydrogen valley in Cyprus?

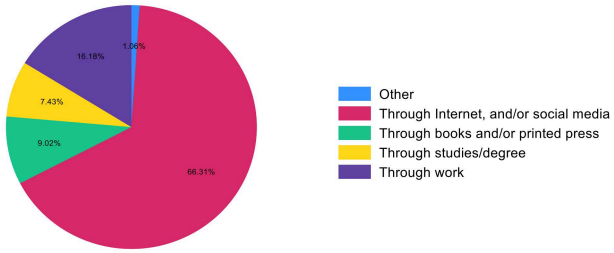


Figure A7. How willing would you be to join in some discussions or activities related to the creation of a hydrogen valley in Cyprus?

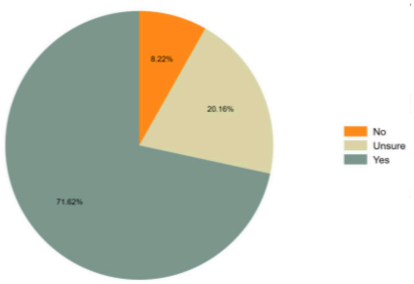
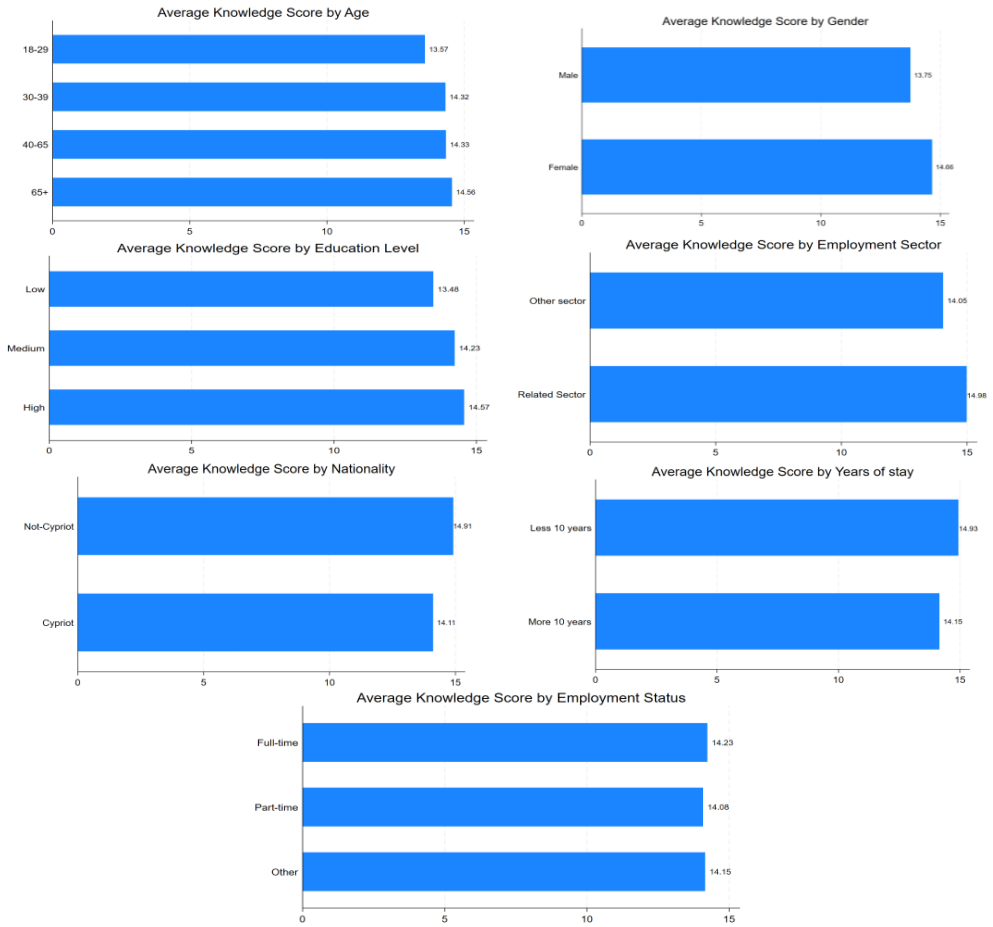


Figure A8. Are you interested to know about hydrogen in energy transition?

Appendix C

The Descriptive Statistics of the Hydrogen Knowledge Score Variable

The minimum score that we obtained was 6, while the maximum score was equal to 22. The average score for our 378 respondents was equal to 14.21.



Higher scores across groups were found for those older than 65 years (14.56), females (14.66), highly educated individuals (14.57), related-sector employment (14.98), full-time workers (14.23), non-Cypriots (14.91), and those who had lived in Cyprus for less than 10 years (14.93). Comparing the knowledge scores across these groups, we see that higher scores are found for those who worked in sectors with many H_2 applications, had lived in Cyprus for less than 10 years and were not Cypriots.

References

1. European Commission. *A Hydrogen Strategy for a Climate-Neutral Europe*; Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions; European Commission: Brussel, Belgium, 2020.
2. NECP. Cyprus' Integrated National Energy and Climate Plan for the Period 2021–2030. Available online: https://meci.gov.cy/en/useful-information/strategic-planning/cyprus-integrated-national-energy-and-climate-plan-for-the-period-2021-2030 (accessed on 22 November 2023).
3. Kakoulaki, G.; Kougias, I.; Taylor, N.; Dolci, F.; Moya, J.; Jäger-Waldau, A. Green Hydrogen in Europe—A Regional Assessment: Substituting Existing Production with Electrolysis Powered by Renewables. *Energy Convers. Manag.* **2021**, *228*, 113649. [CrossRef]
4. Trinomics. *Opportunities for the Inclusion of Hydrogen Technologies in the National Energy & Climate Plans*; Trinomics: Brussels, Belgium, 2020.
5. European Commission. *Joint Declaration on Hydrogen Valleys Moving the Hydrogen Economy from Niche to Scale*; European Commission: Brussel, Belgium, 2023.
6. López, C.R.; Pérez Garcés, L.F.; Tepordei, D.; Moreno, S.P.; Šljukić, B.; Santos, D.M.F. Chapter 14—Challenges in Scaling Low-Carbon Hydrogen Production in Europe. In *Solar-Driven Green Hydrogen Generation and Storage*; Srivastava, R., Chattopadhyay, J., Santos, D.M.F., Eds.; Elsevier: Amsterdam, The Netherlands, 2023; pp. 287–319. ISBN 978-0-323-99580-1.
7. Vivanco-Martín, B.; Iranzo, A. Analysis of the European Strategy for Hydrogen: A Comprehensive Review. *Energies* **2023**, *16*, 3866. [CrossRef]
8. McWilliams, B.; Zachmann, G. Renewable Hydrogen in Germany, Poland, and Portugal. Available online: https://www.euki.de/en/euki-publications/greening-h2-policy-brief/ (accessed on 16 January 2025).
9. Quitzow, R.; Triki, A.; Wachsmuth, J.; Garcia, J.F.; Kramer, N.; Lux, B.; Nunez, A. *Mobilizing Europe's Full Hydrogen Potential: Entry-Points for Action by the EU and Its Member States*; HYPAT Discussion Paper 05/2023; Fraunhofer ISI: Karlsruhe, Germany, 2023.
10. Wolf, A. The Spatial Evolution of a European Hydrogen Economy. *Environ. Policy* **2023**, *58*, 111–118. [CrossRef]
11. Majka, A.; Klimczyk, M.; Kucharski, K.; Muszyńska-Pałys, J. Hydrogen Valley as a Hub for Technological Cooperation Between Science, Business, Local Government and NGOs. An Overview of Approaches in Europe. *Torun Int. Stud.* **2023**, *1*, 5–15. [CrossRef]
12. Notteboom, T.; Haralambides, H. Seaports as Green Hydrogen Hubs: Advances, Opportunities and Challenges in Europe. *Marit. Econ. Logist.* **2023**, *25*, 1–27. [CrossRef]
13. Sgaramella, A.; Pastore, L.M.; Lo Basso, G.; de Santoli, L. Optimal RES Integration for Matching the Italian Hydrogen Strategy Requirements. *Renew. Energy* **2023**, *219*, 119409. [CrossRef]
14. Kafetzis, A.; Bampaou, M.; Kardaras, G.; Panopoulos, K. Decarbonization of Former Lignite Regions with Renewable Hydrogen: The Western Macedonia Case. *Energies* **2023**, *16*, 7029. [CrossRef]
15. Escribano, G.; Urbasos, I. *Spain's Hydrogen Ambition: Between Reindustrialisation and Export-Led Energy Integration with the EU*; Zabanova, Y., Quitzow, R., Eds.; Research Institute for Sustainability: Potsdam, Germany, 2023; pp. 4–22. [CrossRef]
16. Ćetković, S.; Stockburger, J. *Hydrogen Strategy of Sweden: Unpacking the Multiple Drivers and Barriers to Hydrogen Development*; Research Institute for Sustainability: Potsdam, Germany, 2023. [CrossRef]
17. Zhang, Y.; Tang, X.; Xu, S.; Sun, C. Deep Learning-Based State-of-Health Estimation of Proton-Exchange Membrane Fuel Cells under Dynamic Operation Conditions. *Sensors* **2024**, *24*, 4451. [CrossRef]
18. Wu, H.; Zhang, R.; Zhu, W.; Xie, C.; Li, Y.; Yang, Y.; Guo, B.; Li, C.; Xiong, R. A Health Index-Based Approach for Fuel Cell Lifetime Estimation. *iScience* **2024**, *27*, 110979. [CrossRef]
19. Huan, Z.; Sun, C.; Ge, M. Progress in Profitable Fe-Based Flow Batteries for Broad-Scale Energy Storage. *WIREs Energy Environ.* **2024**, *13*, e541. [CrossRef]
20. Kumar, N.; Lee, S.-Y.; Park, S.-J. Advancements in Hydrogen Storage Technologies: A Comprehensive Review of Materials, Methods, and Economic Policy. *Nano Today* **2024**, *56*, 102302. [CrossRef]
21. Meng, X.; Sun, C.; Mei, J.; Tang, X.; Hasanien, H.M.; Jiang, J.; Fan, F.; Song, K. Fuel Cell Life Prediction Considering the Recovery Phenomenon of Reversible Voltage Loss. *J. Power Sources* **2025**, *625*, 235634. [CrossRef]

22. Frankowska, M.; Cheba, K. Exploring the Research Landscape of Hydrogen Valleys: A Bibliometric Analysis. *J. Sustain. Dev. Transp. Logist.* **2023**, *8*, 348–359. [CrossRef]
23. Hodson, M.; Marvin, S.; Simpson, V. Technological Transitions and Public Engagement: Competing Visions of a Hydrogen Fuel Station. In *Risk and the Public Acceptance of New Technologies*; Flynn, R., Bellaby, P., Eds.; Palgrave Macmillan: London, UK, 2007; pp. 198–220. ISBN 978-0-230-59128-8.
24. Flynn, R.; Ricci, M.; Bellaby, P. The Mirage of Citizen Engagement in Uncertain Science: Public Attitudes towards Hydrogen Energy. *Int. J. Sci. Educ. Part B* **2011**, *1*, 97–114. [CrossRef]
25. Flynn, R.; Bellaby, P.; Ricci, M. The Limits of Upstream Engagement in an Emergent Technology: Lay Perceptions of Hydrogen Energy Technologies. In *Renewable Energy and the Public*; Routledge: Oxfordshire, UK, 2010; ISBN 978-1-84977-670-7.
26. Fritz, L.; Baum, C.M.; Low, S.; Sovacool, B.K. Public Engagement for Inclusive and Sustainable Governance of Climate Interventions. *Nat. Commun.* **2024**, *15*, 4168. [CrossRef]
27. Bănică, B.; Patrício, L.; Miguéis, V. Citizen Engagement with Sustainable Energy Solutions—Understanding the Influence of Perceived Value on Engagement Behaviors. *Energy Policy* **2024**, *184*, 113895. [CrossRef]
28. Gordon, J.A.; Balta-Ozkan, N.; Nabavi, S.A. Homes of the Future: Unpacking Public Perceptions to Power the Domestic Hydrogen Transition. *Renew. Sustain. Energy Rev.* **2022**, *164*, 112481. [CrossRef]
29. Gordon, J.A.; Balta-Ozkan, N.; Nabavi, S.A. Beyond the Triangle of Renewable Energy Acceptance: The Five Dimensions of Domestic Hydrogen Acceptance. *Appl. Energy* **2022**, *324*, 119715. [CrossRef]
30. European Commission, Directorate-General for Energy; Brenner-Fließer, M.; Rikos, E.; Tuiskula, H.; Höffken, J.I.; Birch Riley, L.; Kuivalainen, M.; Ktenidis, P. Exploration of Citizen Engagement Methodologies in European R&I Projects 3.0: Consumer, Citizen & Engagement Working Group: June 2023. Publications Office of the European Union. Available online: https://data.europa.eu/doi/10.2833/78191 (accessed on 18 September 2024).
31. European Commission, Directorate-General for Energy; Herbemont, S.; Höffken, J.; Ktenidis, P.; Roberts, J.; Birch Riley, L.; Rikos, E.; Moustafelou, I.; Tuiskula, H.; van Velzen, L.; et al. Exploration of Citizen Engagement Methodologies in European R&I Projects: Consumer & Citizen Engagement Working Group. Publications Office of the European Union. Available online: https://data.europa.eu/doi/10.2833/536458 (accessed on 18 September 2024).
32. Consumer and Citizen Engagement | Bridge. Available online: https://bridge-smart-grid-storage-systems-digital-projects.ec.europa.eu/working-groups/consumer-and-citizen-engagement (accessed on 18 September 2024).
33. Beauchampet, I.; Walsh, B. Energy Citizenship in the Netherlands: The Complexities of Public Engagement in a Large-Scale Energy Transition. *Energy Res. Soc. Sci.* **2021**, *76*, 102056. [CrossRef]
34. Obenaus-Emler, R.; Lehner, M.; Murphy, M.; Pacher, C. Educational Concept for Citizens' Awareness Towards Technological Advancements for a Sustainable Society—Introducing a Concept for Interactive Societal Learning on Hydrogen and Carbon. *BHM Berg-Hüttenmänn. Monatshefte* **2021**, *166*, 314–322. [CrossRef]
35. Eliades, F.; Doula, M.K.; Papamichael, I.; Vardopoulos, I.; Voukkali, I.; Zorpas, A.A. Carving out a Niche in the Sustainability Confluence for Environmental Education Centers in Cyprus and Greece. *Sustainability* **2022**, *14*, 8368. [CrossRef]
36. Freeman, R.E. *Strategic Management: A Stakeholder Approach*; Pitman: London, UK, 1984; ISBN 978-0-273-01913-8.
37. Friedl, C.; Reichl, J. Realizing Energy Infrastructure Projects—A Qualitative Empirical Analysis of Local Practices to Address Social Acceptance. *Energy Policy* **2016**, *89*, 184–193. [CrossRef]
38. Schweizer-Ries, P. Energy Sustainable Communities: Environmental Psychological Investigations. *Energy Policy* **2008**, *36*, 4126–4135. [CrossRef]
39. Arnstein, S.R. A Ladder Of Citizen Participation. *J. Am. Inst. Plann.* **1969**, *35*, 216–224. [CrossRef]
40. Kumar, V. *101 Design Methods: A Structured Approach for Driving Innovation in Your Organization*; John Wiley & Sons: Hoboken, NJ, USA, 2012; ISBN 978-1-118-08346-8.
41. Stalker, L.; Roberts, J.J.; Mabon, L.; Hartley, P.G. Communicating Leakage Risk in the Hydrogen Economy: Lessons Already Learned from Geoenergy Industries. *Front. Energy Res.* **2022**, *10*, 869264. [CrossRef]
42. Long, J.S.; Freese, J. *Regression Models for Categorical Dependent Variables Using Stata*; Stata Press: College Station, TX, USA, 2014; ISBN 978-1-59718-111-2.

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Impact of Inclusive Growth, Environmental Policy Incentives, Fintech and Globalization on Environmental Sustainability in G20 Countries

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Abstract: This research investigates the effects of inclusive growth, environmental policy incentives, fintech innovations, and globalization on the environmental sustainability of G20 countries. In light of the growing global concern about carbon emissions from anthropogenic sources, which contribute to severe environmental degradation, the Paris Agreement aims to mitigate these impacts by controlling carbon emissions. This study explores how inclusive growth, fintech, and environmental policies interact to affect ecological footprints in G20 member countries, which represent some of the world's most influential economies and policymakers. Specifically, inclusive growth is examined for its potential to reduce economic and social inequalities, which, if unmanaged, can exacerbate environmental degradation. In contrast, fintech is analyzed as a double-edged sword—its impact on sustainability depends on its influence on industries and economies, which may either exacerbate or alleviate environmental harm. Globalization's role is scrutinized for its interactions with the economic, social, and ecological dimensions of sustainability. Our methodology employs advanced econometric models to analyze data from 1990 to 2023, focusing on the relationships between these variables and ecological footprints. Key findings suggest that while fintech can both increase and reduce environmental degradation depending on its application, environmental policy incentives are crucial for promoting sustainable practices and clean technology adoption. Inclusive growth can mitigate environmental harm by addressing inequalities, and globalization's effects on sustainability depend largely on regulatory frameworks and corporate governance. This study contributes to the literature by highlighting the complex interactions between economic growth models, technological advancements, and environmental policies. Its originality lies in its comprehensive analysis of the G20 economies, shedding light on how inclusive growth, fintech, and environmental policies shape environmental outcomes. The research offers key policy implications, stressing the need for stringent environmental regulations, the promotion of green technologies, and the diversification of economies to reduce reliance on resource rents. The findings emphasize the importance of balancing economic development with environmental sustainability to achieve long-term ecological stability.

Keywords: environmental sustainability; G20 countries; inclusive growth; environmental policy incentives; clean technology investment

1. Introduction

The world's anxiety over the dramatic rise in anthropogenic carbon emissions, which have increased by approximately 66% from 22.73 billion tons in 1990 to 37.79 billion tons in 2023, as per Our World in Data, is increasing [1–4]. There are some examples of

international agreements that have been made possible by multiple countries, like the Kyoto Protocol, the Paris Agreement and the United Nations Framework Convention on Climate Change (UNFCCC). These accords point to the need to cut back the amount of manmade carbon that is released into the atmosphere to protect the global ecosystem from changes in climate due to increasing sea and temperatures, floods and drought, wildfires and so on. For example, between about 1750 and 1850, the average world temperature increased by about 1.0 to 1.2 degrees Celsius above the preindustrial baseline [4]. Similarly, globally, the sea level has risen comparably by 21–24 cm since 1880 [5]. Under the forecast of the Intergovernmental Panel on Changes in the Climate, the average global temperatures at the end of the twenty first century are expected to increase by 1.8 °C to 5.8 °C, and the average global sea levels are expected to increase by 9 to 88 cm [6]. This contrasts with the background, as empirical study of the root causes of malicious emissions has become the focus of increasing international debate. This is because identifying the specific causal factors of environmental degradation is a prerequisite to adopting new approaches for mitigating the hazards of climate change [7].

This being the case, environmental policies must provide incentives that will encourage more environmentally sustainable practices and behavior. Acknowledging the works of Acemoglu and Rafey, the center of gravity of existing research in this area is the relationship between environment policies and reduced emissions [8] (Greenstone, He) [9]. By offering informational, financial and regulatory incentives, lawmakers are hoping to persuade people, companies and governments to adopt 'green' habits and technologies. Renewable energy projects are one example of how clean technology incentives can encourage investors to maximize capacity investment and minimize reliance on fossil fuels while moderating carbon emissions and increasing the flow of sustainable energy [10]. Examples include policies of emissions trading schemes and taxes on pollution, which give businesses financial incentives to reduce their environmental effect and absorb the costs of pollution [11]. And on the other hand, informational incentives can provide consumers with useful and detailed information to help them make judicious choices and increase the demand for environmentally friendly products and services. Two of these include public awareness campaigns and the use of eco labeling [12]. These policy incentives are collectively geared towards facilitating the transition towards a society that is environmentally conscious and as concerned with ecological issues as it is with economic growth.

In addition, inclusive growth policies promote equitable economic growth, and sustainable environmental policies promote the preservation of long-term ecological health. Inclusive growth, as a developmental approach, seeks to ensure that the benefits of economic progress are broadly shared across all segments of society, addressing disparities in income, education, and access to resources. It is often viewed as a pathway to reducing economic and social inequality, fostering social cohesion and stability. However, it presents a paradox: while it can uplift marginalized communities and enhance economic opportunities, it may simultaneously exert pressure on natural resources, leading to accelerated ecological deterioration. The dual nature of inclusive growth necessitates innovative policy frameworks that can balance the demands for equity and sustainability [13]. Knowing how humanity and natural processes are related is vital for creating policies that maintain economic prosperity while still protecting our environment.

For academics, the complicated relationship between technological innovations and their consequences on the environment poses a paradox: while defining advances normally leads to greater carbon emissions, fintech has begun to emerge as a disruptor. Fintech has the ability to revolutionize business through its creative combination of big data and computer intelligence and reshape industries by reducing their carbon output and potentially pushing them in a more environmentally friendly direction [14]. In addition, fintech

enables economic growth and this enables the growth of technology but, concomitantly, carbon emissions are likely to rise. Because fintech has the potential to both worsen and lessen environmental effects, its effect on carbon emissions is still unknown. Concurrently, the fusion of growing economies and digital tech has birthed a new commercial framework, boosting efficiency. Fintech's rapid evolution further drives digital transformation in commercial institutions [15,16].

Moreover, fintech establishes a platform for ecological services, leveraging data from information technology to enhance customer understanding within the fintech framework. This allows for the optimization of upstream and downstream resources and improves the efficiency of underutilized resources. The framework facilitates the development of innovative methods for waste recycling and resource optimization, reducing the depletion and environmental pollution associated with continuous manufacturing processes and ultimately leading to a decrease in carbon emissions [17]. When it comes to the availability of business services, fintech is thought to help the marginalized population that traditional financial institutions overlook in terms of basic needs. It also promotes economic growth and raises the incomes of underprivileged communities. Fintech's involvement will encourage businesses and private investors to provide funding with consideration of mitigation technologies [18]. Mitigation technology stands to gain significant support, potentially alleviating ecological pressures. Local green growth can be achieved by better allocating social resources using a commercial framework. By reducing asymmetric information between businesses and commercial institutions, fintech typically reduces the cost of green recognition and risk valuation for commercial institutions, promoting the expansion of green finance [19].

Globalization, with its intricate web of causes and consequences, sparks diverse interpretations among scholars, each shaped by their unique disciplinary lenses and worldview perspectives [20,21]. Globalization is the intensified cross-national interactions fostering global integration across various dimensions, including cultural, economic, ecological, political, technological, and social processes [22]. Countries that are more globally integrated put more strain on ecosystems both locally and globally, which can be harmful to sustainability. As a result, the nations with the highest levels of globalization might not be the most sustainable. Globalization indices by themselves are insufficient to shed light on the advantages or disadvantages of globalization. The necessity to evaluate the effects of globalization on sustainability indicators in the ecological, economic, and social spheres is becoming more and more pressing [23]. While a positive correlation between Globalization Indices and sustainability indicators might seem promising, it is crucial to recognize that the sustainability of globalization does not uniformly benefit all nations. It becomes necessary to weigh trade-offs, since sustainable development in one context could not coincide with sustainability in another. In an ideal world, globalization would promote steady advancement in all economies, civilizations, and ecologies. But doing all three at once is still a lofty goal, underscoring the complexity of the relationship between globalization and sustainability [24]. Few sustainability concerns in the modern era compare to the increasing stress on ecosystems caused by human demands, measured as environmental footprints. The overwhelming body of information highlights the urgent need for radical changes in the way humans are organized around the world and presents a clear picture of how unsustainable the current course of humankind is [25].

Today, examining the effects of globalization, fintech, inclusive growth, and environmental policy incentives on environmental sustainability in G20 nations is more important than ever. This comes at a time when environmental problems are worsening daily, as pollution and climate change lead to a loss of biodiversity, and as the world is coming to acknowledge sustainable development as the only way of addressing the above problems affecting current as well as future generations. The member countries are collectively

known as G20. They comprise a large share of the world's population and are major contributors to the global economy; thus, the decisions of these countries have a large impact on global rules and regulations. Hence, the purpose of this research is to identify the role of various factors in the sustainability of environments in these countries. These factors include globalization interconnectivity, the fin techs that are revolutionizing the commercial realm, and inclusive growth, which aims to offer fairness in the economic developments and the bonuses given by environmental laws that are meant to push for environmentally sustainable activities. An extensive and vast array of policies, corporations, and civil societies can locate more practical approaches on how these relationships affect the environment and consider how to best balance economic growth and the provision of environmental conservation. And because many global challenges are interconnected today, knowledge of the dynamics of the sustainability of the environment within the G20 countries may be useful, allowing us to focus on other actions for the advancement of environmental problems around the world.

We travel through several sections in this work, each providing unique perspectives and contributions. To broaden our perspective and situate our study within a broader body of knowledge, Section 2 serves as our compass by providing a detailed examination of the corpus of previous research. Our theoretical framework and meticulously crafted model specifications are presented in Section 3, providing the groundwork for our empirical inquiry. Numerous data, resources, and approaches are provided in Section 4. Our project's primary activity occurs in Section 5, where we present our findings and engage in discussion. Section 6 represents the culmination of our journey, whereby we present compelling policy implications and draw noteworthy conclusions from our analysis.

2. Literature Review

As economies expand, they frequently fail to consider the environmental costs associated with such growth, which contribute to pollution and resource depletion. The shift to the green economy is necessary, especially when addressing the emerging dependencies on natural resources, a vision of sustainable progress. However, growth alone is insufficient to create large-scale improvements; only inclusive growth can ensure that no one is left behind during economic development, particularly when considering how to conserve the environment for future generations. Inclusive growth with sustainability can lead to a better and greener future, as revealed by Xue, Shahbaz [26]. Focusing specifically on inclusive growth, Kamah, Riti [13] also pointed out that growth could be linked to the environment in numerous ways. This emphasis highlights the degree to which strong governance is crucial when promoting the connection between development and sustainability.

Further, the concept of the environmental inclusive-growth Kuznets curve is introduced, which suggests that environmental degradation worsens in the earlier stages of inclusive growth but improves with further progression of inclusive growth. This theoretical framework contributes to understanding how economies can balance growth and environmental health. Pham, Lin [27] explored the complex relationships between natural resource rents, financial development, and inclusive growth in Asia's economic giants, offering fascinating insights. The results underscore the pivotal role that natural resource rents and financial development play in fostering inclusive growth and economic advancement. However, they caution that population growth may negatively correlate with inclusive growth, signaling potential difficulties ahead. This nuanced understanding of the intricate interrelationships influencing inclusive growth in Asian countries provides a foundation for informed policy decisions and strategic interventions aimed at promoting equitable and sustainable development.

2.1. Fintech and Environmental Sustainability

Fintech is critical for environmental sustainability due to its potential to expedite transactions, promote green funding, and incentivize eco-friendly behaviors across industries. The correlation between technology, natural resources, and carbon emissions among OECD nations presents intriguing findings, as scrutinized by He, Jie [28]. Their results indicate a positive association between fintech innovation and reduced emissions, confirming that financial contributions play a crucial role in sustainable development. However, the findings also highlight that rising emissions are associated with increasing natural resource rents, suggesting that escalating economic activity exacerbates the harmful effects of climate change.

Following this, Feng, Chong [29] analyzed the ecological impact of digital financial development across China's provinces. Their research demonstrates that digital banking effectively reduces environmental impacts while promoting ecological conservation and economic growth. Reducing the digital divide and strengthening environmental laws would enhance the effectiveness of digital banking. Green technology innovation and green finance are vital for environmentally friendly growth, with financial technology facilitating sustainable development and reducing environmental harm. In this context, Lisha, Mousa [30] investigated the relationship among natural resources, financial development, fintech, and sustainability in the BRICS countries. Their findings show that environmental sustainability is negatively impacted by fintech and natural resources across all three quantile ranges. However, economic expansion leads to higher emissions at lower quantiles, while financial development supports environmental sustainability across all quantiles.

Fintech consistently reduces ecological footprints, especially in higher-deficit scenarios, while ecological governance helps reduce footprints in most quantiles, except for the largest, as evaluated by Xia and Liu [31] for G7 nations. Natural resources, however, tend to increase ecological footprints, especially at higher quantiles. Panel causality analysis reveals a bidirectional relationship between natural resources, economic growth, and ecological footprints, while a unidirectional causality exists between fintech, environmental regulations, and footprints. In their study of the USA's ecological footprint, Ali, Joof [32] demonstrated that while natural resources degrade environmental quality, renewable energy sources help improve it. Furthermore, their research supports a strong correlation between technological innovation and improved ecological quality.

Shu, Usman [33] investigated the immediate and long-term relationships between China's greenhouse gas emissions, natural resources, and fintech services using dynamic autoregressive distributed lag (DARDL) simulations. They found that renewable energy reduces pollution in the short term, and both fintech and renewable energy contribute to reduced carbon emissions in the long term. Conversely, urbanization and natural resources contribute to both short- and long-term increases in carbon emissions. Additionally, economic growth raises greenhouse gas emissions over time while exacerbating environmental damage in the short term.

Feng and Li [15] explored the relationship between fintech, natural resources, environmental taxes, urbanization, and environmental sustainability within the ASEAN-6 economies. Their results indicate that natural resources are a major source of CO_2 emissions, while finance and environmental taxes play mitigating roles. Urbanization, however, is found to be the primary driver of ecological degradation. Their outcomes indicate a bidirectional causal relationship between environmental quality and environmental taxes.

2.2. Globalization, Financial Development, and Environmental Sustainability

Globalization has the potential to reduce carbon emissions, but financial development tends to elevate them, as analyzed by Tahir, Luni [34] in a study focused on South Asian

economies. They found evidence of a unidirectional causal relationship between emissions and environmental degradation caused by financial development, globalization, and economic growth. Government oversight is essential to ensure that loans are directed toward research and development, green funding, and efficient production processes, safeguarding sustainability without compromising environmental health. This could help reduce resource consumption while improving environmental quality.

Duttagupta, Lizarazo Ruiz [35] focused on the implications of globalization and inclusive growth in low-income developing countries (LIDCs), with a specific emphasis on Ghana in the early 1990s. Their findings revealed that Ghana's efforts to reduce poverty and achieve economic growth were significantly aided by globalization and liberalization. However, disparities emerged due to the disproportionate distribution of benefits, which were attributed to limitations in labor mobility and differences in skill levels. This resulted in a widening income gap, particularly among those who benefited from better access to financial and human capital, highlighting the challenge of achieving equitable growth.

Aluko, Opoku [7] examined the impact of globalization on environmental degradation in 27 developed countries. They specifically analyzed the effects of the political, social, and economic facets of globalization and their influence on environmental deterioration. The results showed that while social and political globalization had no significant impact, economic globalization reduced environmental degradation. Moreover, the study found that actualized economic globalization helped lessen environmental degradation, while de facto globalization, when combined with social globalization, also contributed to environmental preservation.

2.3. Contributions to the Literature and Research Gaps

Despite extensive research on environmental sustainability, several gaps remain. First, while prior studies have examined globalization, technological advancements, and environmental policies individually, their interactive and dynamic effects on ecological outcomes, particularly within the context of G20 economies, remain insufficiently explored. Second, the role of financial development, particularly fintech, in moderating the relationship between economic growth and environmental sustainability is under-researched, with limited empirical evidence on its balancing potential. Finally, most existing studies rely on static models, which fail to capture the heterogeneity and time-dependent effects of key factors influencing environmental quality.

This study addresses these gaps by employing robust econometric techniques, including Driscoll–Kraay standard error estimations to address cross-sectional dependence and Generalized Method of Moments (GMMs) for addressing endogeneity and dynamic relationships. By integrating these advanced methodologies, this research provides a nuanced understanding of the time-varying effects of globalization, fintech, and policy incentives on environmental sustainability in G20 countries. This novel approach enhances both the empirical and theoretical literature, offering actionable insights for policymakers to balance economic development with ecological preservation.

3. Theoretical Framework

Ehrlich and Holdren [36] initiated a mission to disentangle the complex web of human influence on the environment when they presented a ground-breaking tool, the impacts (I) by regression on population (P), affluence (A), and technology (T) called (IPAT) model and that is given below:

$$I = PAT \tag{1}$$

Imagine if human activity—population dynamics, economic success, and technological prowess—were represented by individual brushstrokes on a canvas, each of which

combined to create the environment. These components are now linked forces bringing about change rather than isolated strands because of IPAT. Consider the environment as a stage with technology, wealth, and demographics as the main players, each of whom is vital to the spectacle of environmental impact developing. By removing layers of complexity and exposing hidden patterns of human–environment interaction, Ehrlich and Holdren's model challenges us to decipher this story. Not only is it an equation, but it also offers us a glimpse into the complex relationship between nature and society, inviting us to consider the implications of our collective activities. Based on the main mechanisms behind anthropogenic environmental impressions in the early 1970s, it is widely used to analyze the forces that significantly impact environmental alteration [3,37–40].

Like any other tool, the IPAT model has limitations. The idea that changes in population, wealth, and technology will all have the same effect on the environment is one of its most significant limitations. To put it another way, it implies that all the factors have equal influence over the state of the ecosystem. Reality is much more complex, though. Dietz and Rosa [41] intervened, providing an in-depth analysis to rectify these deficiencies. They developed the stochastic impacts by regression on technology, affluence, and population (STIRPAT) framework as an extension of the model and it can be written as follows:

$$I_{it} = \dot{\eta} P_{it}^{\alpha} + A_{it}^{B} + T_{it}^{\gamma} + \varsigma_{it} \tag{2}$$

This can be seen as a refined version that aims to convey the dynamism of the environment's unexpected nature. STIRPAT recognizes the variation in each factor's impact rather than viewing them as equal participants. The model offers a more realistic picture of how population, wealth, and technology influence environmental outcomes by including stochastic aspects, or variables that are subject to chance or unpredictability. It is like shifting the focus to emphasize the intricacies and minute variations in human influence on the environment.

The IPAT model's assumption that each macroeconomic element has an equal weighting on the environment is relaxed in the STIRPAT model. The subscripts i and t, respectively, stand for the cross-sections and temporal dimensions in Equation (2). The symbols $\dot{\eta}$ and ς_{it}, respectively, have been used to indicate the constant and error terms. The parameters α, B, and γ, as well, denote the coefficients of P, A, and T. By taking the natural logarithm, the aforementioned STIRPAT model can be translated and linearized as follows:

$$lnI_{it} = \dot{\eta} + \alpha lnP_{it} + BlnA_{it} + \gamma lnT_{it} + \varsigma_{it} \tag{3}$$

3.1. Model Specification

In our quest to understand the impact of inclusive growth, environmental policy incentives, fintech, and globalization on environmental sustainability within the G20 nations, we have devised a comprehensive approach. By incorporating ecological footprint as our dependent variable, we aim to unravel the intricate web of factors influencing environmental well-being. Alongside traditional metrics like inclusive growth and economic globalization, we delve into novel dimensions such as fintech adoption, natural resource rent, and urbanization levels. Our empirical model, augmented with Equation (3), serves as a powerful tool to uncover the dynamics shaping our planet's ecological future and is as follows:

$$lnEF_{it} = \beta_0 + \beta_1 lnIG_{it} + \beta_2 lnTNR_{it} + \beta_3 lnGI_{it} + \beta_4 lnFI_{it} + \beta_5 lnEPS_{it} + \beta_6 lnURB_{it} + \varepsilon_{it} \tag{4}$$

In the above Equation (4), EF is ecological footprint which is a dependent variable, and the rest of the variables are independent variables which include IG (inclusive growth), TNR (total natural resource rent), GI (globalization), FI (fintech index), EPS (environmental

policy stringency) and URB (urbanization). β_1, β_2, β_3, β_4, β_5, β_6 are the coefficients of the independent variables. ln shows the log and ε is the error term.

Hence, through rigorous analysis, this study seeks to illuminate the intersections where economic development, technological advancements, and global interconnectedness intersect with environmental well-being. Ultimately, it endeavors to offer insights that can inform policy decisions and sustainable practices for a more harmonious coexistence between human society and the environment.

3.2. Data and Variables Description

This study makes use of a panel time series dataset that comprises the G20 nations: the United States, Saudi Arabia, South Africa, Turkey, Argentina, Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Italy, Japan, Republic of Korea, Mexico, and the Russian Federation. The years 1990–2023 are included in the dataset. The Global Footprint Network (2022) provided the ecological footprint (EF) data.

Data on fintech, natural resources, urbanization, and inclusive growth were given by the WDI (2022).

The KOF Swiss Economic Institute is the source of the globalization index data (SEI, 2022). Gygli, Haelg [42] state that the globalization index has a score range of 1 to 100, where higher values correspond to a greater level of globalization. One of the primary explanatory variables is fintech; its index was developed by using Principal Component Analysis (PCA) of three variables extracted from the WDI (2022).

In accordance with the research conducted by Xu, Zhang [43], Tan, Yasmeen [44], and Emara [45], three factors—mobile cellular subscriptions, fixed broadband subscriptions (per 100 persons), and users of internet as a proportion of the population—are used to calculate fintech. Information and communication technology (ICT) is the core component of the fintech sector. Fintech, which leverages ICT infrastructure, creates feasible innovations that are transforming traditional financial services, such as digital wallets, crowdfunding websites, and online banking.

The fintech business has grown rapidly, promising to provide technology that will enhance and transform finance through more sophisticated ICT systems and computational tools.

GDP per person employed is a measure of inclusive growth [46,47], whereas urbanization is determined by the percentage of the population living in urban areas [48–50]. Globalization is measured by the KOF globalization index [50–52], environmental policy stringency is measured by the environmental policy stringency index [53–58] and the total natural resource rents (as a percentage of GDP) are used to calculate total natural resource rent [50,59]. The definitions of each variable, symbol, and data source used in the study are shown in Table 1.

Table 1. Variables description and sources.

Variables	Symbol	Definitions	Sources
ecological footprint	EF	Global hectares per capita	Global Footprint Network (GFN)
fintech Index	FI	It is constructed by three indicators, namely, i–e % of the population with internet users, mobile cellular subscriptions, and fixed broadband subscriptions (per 100 persons)	WDI
Inclusive Growth	IG	GDP per person employed (constant 2017 USD)	WDI

Table 1. *Cont.*

Variables	Symbol	Definitions	Sources
Urbanization	UR	Urban population (% of total population)	WDI
Globalization	GI	KOF globalization index	SEI, 2022
Environmental Policy Stringency	EPS	Environmental policy stringency index	OECD
Total Natural Resources Rent	TNR	Total natural resources rents (% of GDP)	WDI

3.3. Empirical Techniques

Numerous methodologies, including preliminary testing, unit root tests, cointegration tests, regression tests, and causality tests, were employed in this study.

3.3.1. Preliminary Tests

Cross-Sectional Dependence Test

A Cross-Sectional Dependence (CSD) test's basic principle is to ascertain whether a model's residuals are cross-sectionally dependent. This indicates that rather than being independent observers, the sample members influence one another's results. The first of the numerous initial tests which must be performed prior to looking at the short- and long-term estimates is CSD. CSD can occur because of the link relating the economies owing to trade incorporation, cultural interaction, mutual borders, economic and financial dependency, and common social characteristics [60].

CSD is performed because of the high likelihood of data dependencies among several cross-sectional units. According to Sohail, Ullah [61], one of the main causes of this reliance are a few hidden factors and interconnected shocks that can cause "error term, spatial dependence, and idiosyncratic pairwise dependency" to appear in variations even in the absence of any obvious arrangement of similar characteristics or geographic relationships. Because of their connections in the financial and economic domains, the nations' reliance on one another has grown significantly over the last 20 years, resulting in a high degree of dependency in the cross-sections of the panel data. The choice between first- and second-generation panel unit root tests was supported by a CSD test. To identify the CSD issue, three distinct tests are employed in this study. These are the Pesaran CSD, Pesaran [62], and Breusch and Pagan [63] LM tests. Equation (5) illustrates the CSD test's equation.

$$CD = \sqrt{\frac{2T}{N(N-1)}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{p}_{ij}\right)} \quad (5)$$

where CD is the cross-sectional dependence, N is panel cross-sections, T is the period, and pij is the cross-sectional correlation of errors among i and j.

Slope Heterogeneity Test

In panel datasets, panel heterogeneity refers to the systematic differences or discrepancies between entities or units. It illustrates the changes in the units' traits, behaviors, or relationships along the cross-section. Heterogeneity results from unidentified individual-specific factors or elements that affect the dependent variable. Therefore, in our current study, we have employed the heterogeneity test that is robust to both autocorrelation and heteroscedasticity. The estimate problems caused by individual slope heterogeneity may be found and resolved with the support of a slope heterogeneity test. These problems may involve inaccurate results and inconsistent parameter estimates.

In order to select the tests to be used in cointegration and causality investigations and to accurately evaluate the outcomes, it is necessary to look at the homogeneity of panel data models. The first study of slope coefficient homogeneity in the panel cointegration equation was carried out by Swamy [64]. Afterwards, the Swamy [64] model was enhanced by Pesaran and Yamagata [65]. Depending on the sample size, two types of test statistics were provided by Pesaran and Yamagata [65] in order to evaluate the hypotheses.

Heteroscedasticity Test

The presence of heteroscedasticity suggests that the error term's variance is not constant and might be the result of outliers. Nevertheless, it provides false conclusions and outcomes [66]. According to [67], heteroscedasticity testing is a helpful method for analyzing the relationship among explanatory variables and residual variance. A Breusch–Pagan/Cook–Weisberg test was used.

3.3.2. Unit Root Test (CIPS Test)

Two different kinds of unit-root tests are obtainable to identify the nonstationary problems in panel data estimations. As a result of their inability to account for cross-sectional dependency amongst the variables, the tests developed by Im, Pesaran [68], Levin, Lin [69], and Breitung [70] are instances of the first-generation tests [71]. This causes us to search for stationarity features in the variables using the cross-sectionally augmented IPS (CIPS) test, a second-generation unit root test. Pesaran [72] offers the CIPS test, which is founded on cross-sectionally augmented Dickey–Fuller (CADF) and can be used to control cross-sectional dependency [73]. To make trending data stationary, the CIPS test is utilized to decide whether to use the first difference method on the data or regress them on deterministic functions of time. The analysis of long-term equilibrium connections among nonstationary time series variables is another option.

Verifying the stationarity characteristics of the variables comes next, after the analysis of cross-sectional dependency. Economic interdependence has developed between nations because of globalization in politics, economy, and society. As a result, first-generation stationarity tests are useless as they ignore dimensionality, slope heterogeneity, and CSD effects. Second-generation unit root tests are used to address these kinds of issues. The cross-sectional Im, Pesaran, and Shin (CIPS) test, which overcomes CSD difficulties and takes heterogeneity into consideration, is proposed by Pesaran [71]. Equation (6) reports the results of the CIPS test.

$$CIPS = N^{-1}\sum_{i=1}^{N} \pi_i \ (N, T) \tag{6}$$

In the above equation N = cross-sections and T = time.

3.3.3. Cointegration Test (Westerlund Cointegration Test)

Cointegration is the study of the variables' long-term relationship. Cointegration is necessary for a valid long-term connection among the variables. The Westerlund cointegration test is a reliable panel data test which determines if individual or full panels have an error correction. The basic principles of the test comprise the null hypothesis, which states that cointegration does not exist. The possibility that some or all the panels are cointegrated is the alternate hypothesis. The purpose of the Westerlund cointegration test is to ascertain whether two or more nonstationary time series have a long-term relationship. This method is preferable compared to numerous other cointegration methods, since it can deal with structural breakdowns and CSD problems.

Thus, the panel cointegration method was proposed by Westerlund [74]. This approach really makes a distinction between the variability in the short- and long-term dynamics of cointegration, as noted by Persyn and Westerlund [75]. Moreover, this approach removes

the cross-sectional dependence issue and has an optional bootstrap technique that permits several cointegration test iterations. According to this approach, the alternative hypothesis that there is at least one long-term link should be considered for the group-mean tests (Gt and Ga). Conversely, cointegration within the panel is taken into account as an alternative hypothesis by the panel tests (Pt and Pa) [75].

3.3.4. Regression Test

Driscoll–Kraay (D/K) Standard Errors

To determine the correlations amongst the independent variables and ecological footprint, regression analysis using Driscoll–Kraay standard errors is used. For correct inference, this approach provides robust standard errors and takes heteroskedasticity into consideration. The standard errors are modified to account for probable heteroskedasticity in the data when performing regression analysis with heteroskedasticity-resilient standard errors using the Driscoll–Kraay approach. For a linear regression model with D/K standard errors, the equation takes the following generic form:

$$Y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \cdots \ldots + \beta_k X_{ki} + \varepsilon_i \quad (7)$$

where i represents observation and Yi is the dependent variable. The value of the jth independent variable for the z observation is shown by Xij.

The coefficient of the jth explanatory variable is denoted by βj. ε_i is the error term for i observation.

Generalized Method of Moments (GMMs)

While attempting to estimate regression coefficients, endogeneity appears. Endogenous correlation occurs when there is a relationship among an explanatory (exogenous) variable and the error term [76]. Be advised that this may lead to inaccurate assessments, misunderstandings, and erroneous conclusions. According to Berk, Kasman [77], endogeneity causes bias and conflicting outcomes when employing within-group or panel OLS estimations. Arellano and Bond [78] and Blundell and Bond [79] suggest using the GMM model to study dynamic panel data. In comparison to Mean Group (MG) and Pooled Mean Group (PMG) estimators, the GMM is more appropriate, since it can manage endogeneity, produces reliable and efficient estimates, and is helpful for growth models where N > T. In order to address endogeneity, this dynamic model—also referred to as "internal instruments" [80]—utilized an explanatory variable that was a lagged dependent variable [76]. The GMM subtracted the prior score from the present scores to perform "internal data transformation." It improves efficiency and reduces observations [81]. Two forms of GMM transformations include first-difference transformation (also known as a "one-step GMM") and second-order transformation (sometimes known as a "two-step GMM") [76]. For example, when a variable's most recent value is absent, the one-step GMM loses a lot of data. A two-stage GMM was suggested by Arellano and Bover [82]. The technique, called "forward orthogonal deviations," is based on deducting the weighted average of each consecutive measurement of a particular variable [80]. As a result, it produces useful results in a variety of datasets [82].

Prais–Winsten Regression, Correlated Panels-Corrected Standard Errors (PCSEs)

This research uses a linear regression technique called Panels-Corrected Standard Errors (PCSEs), which was invented by Beck and Katz [83]. When the parameters are calculated using Prais–Winsten regression, this yields panel-corrected standard error estimates for both linear models. The PCSEs approach computes variance–covariance estimates and standard errors while taking cross-panel heteroskedasticity and contemporaneous correlation into

consideration. This estimation technique works best for extended panel datasets, like the one used in this study, where the number of years exceeds the number of panels (T > N).

3.3.5. Causality Test (Pairwise Juodis, Karavias, and Sarafidis Test)

Bootstrapping variance is used to adjust for cross-sectional dependency in the panel Granger causality test for homogeneous or heterogeneous coefficients, developed by Xiao, Karavias [84] and Juodis, Karavias [85]. This method yields N individual-specific Wald statistics, which are subsequently averaged throughout the cross-section, from N individual regressions.

4. Results

These Figures 1–6 show the trend of selected variables used in the study over time.

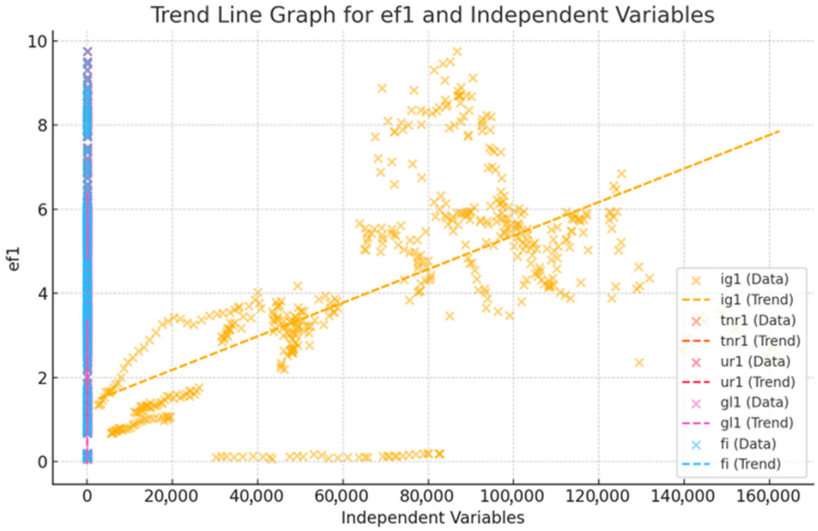


Figure 1. Trend line graph of ef and all independent variables.

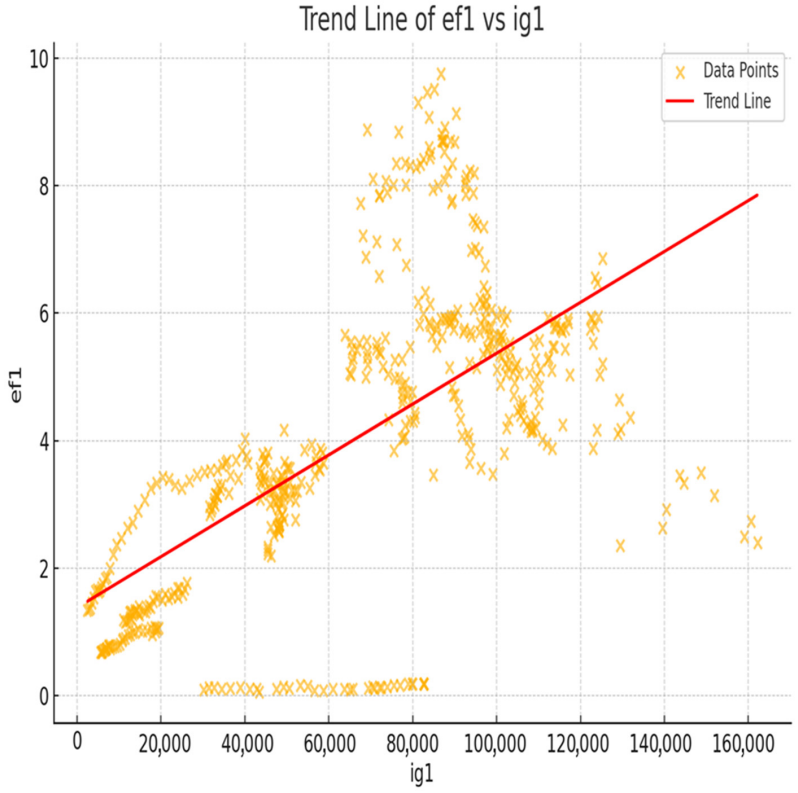


Figure 2. The graph shows the trend line of ef1 with respect to ig1.

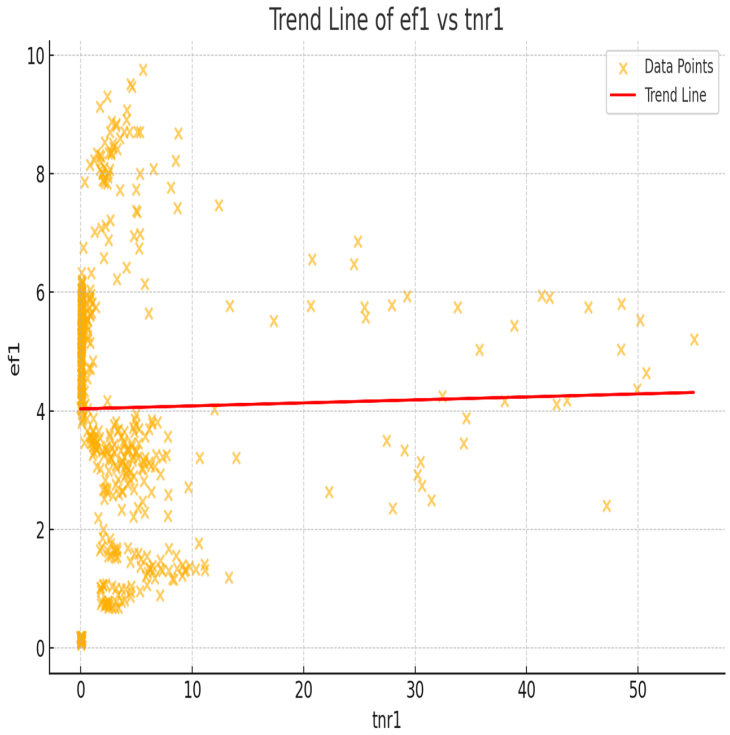


Figure 3. The graph shows the trend line of ef1 with respect to tnr1.

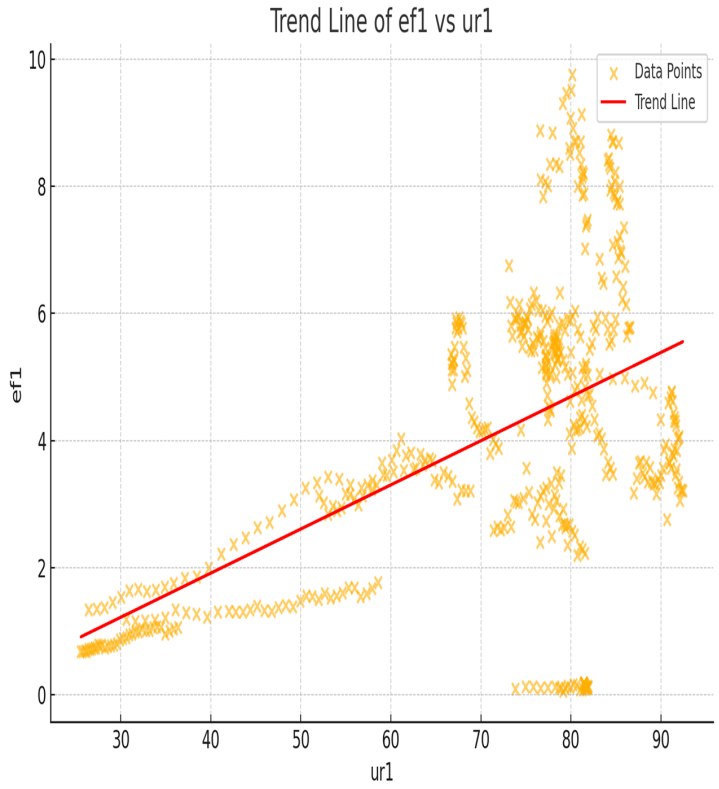


Figure 4. The graph shows the trend line of ef1 with respect to ur1.

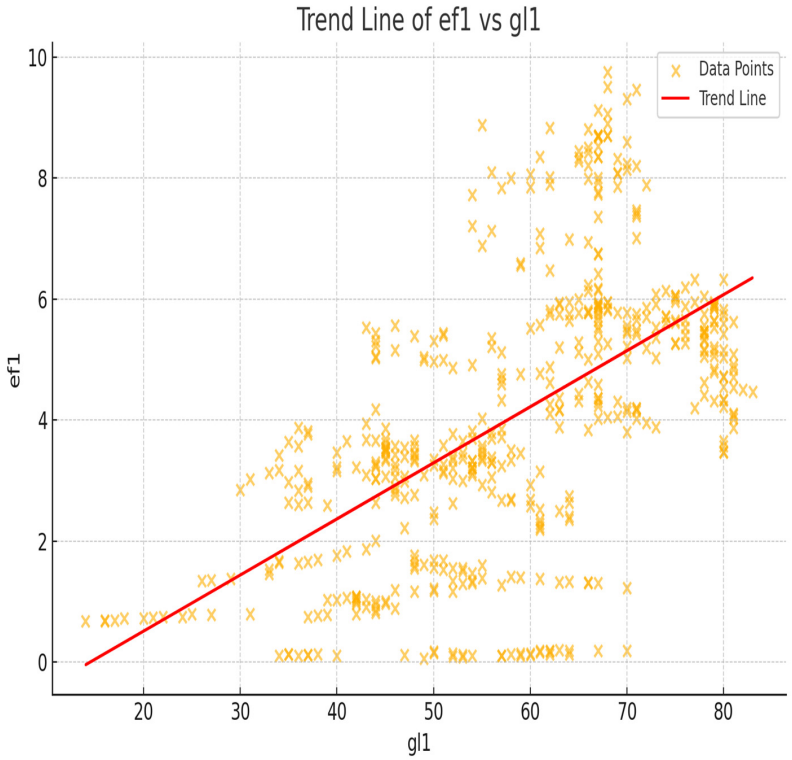


Figure 5. The graph shows the trend line of ef1 with respect to gl1.

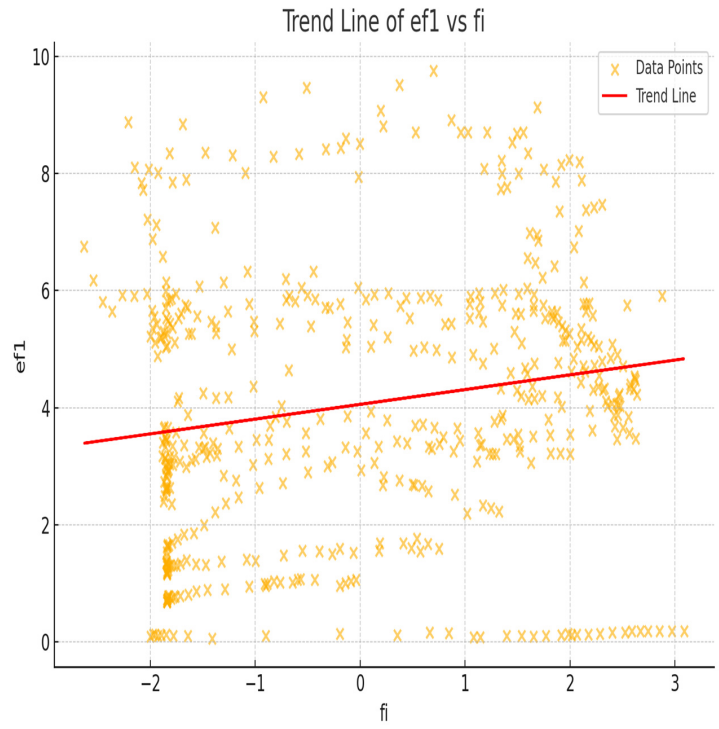


Figure 6. The graph shows the trend line of ef1 with respect to fi.

4.1. Descriptive Analysis

Table 2 provides descriptive information for the variables examined for the G-20 nations. Inclusive growth (IG) has the greatest average value (10.20977), and total natural resource rent (TNR) has the lowest average value (0.727) according to descriptive information data. The fintech index (FI) has an average value of 4.050107, whereas urbanization (UR) has an average value of 17.97. Globalization (GI) has an average value of 1.222. Envi-

ronmental policy stringency (EPS) has an average value (4.023328), and ecological footprint (EF) has an average value (1.720024).

The FI has a min (3.49365) and max (4.365746). UR has a min value of 8.55 and a max value of 100.00. Likewise, the min and max values of IG are 8.504314 and 11.62998. On the other hand, GI and EF have min values of −6.335 and −0.0822707 and max values of 4.126 and 2.875039. EPS and TNR have min values of 3.396999 and −6.2445; however, they have max values of 4.402329 and 3.256. The FI has a sd.dev value of 0.1856814. UR has a sd.dev value of 17.97. The sd.dev. values of IG and GI are 0.619819 and 1.494. EF has a sd.dev. value (0.3316092) and EPS has a sd.dev. value (0.2023284). The standard deviation value of TNR is 1.427.

Table 2. Descriptive statistics.

Panel	Average	Sd. Dev.	Min	Max
Fintech Index (FI) (0–100)				
	4.050107	0.1856814	3.49365	4.365746
Urbanization (UR)				
	76.57	17.97	8.55	100.00
Inclusive Growth (IG)				
	10.20977	0.619819	8.504314	11.62998
Globalization (GI)				
	1.222	1.494	−6.335	4.126
ecological footprint (EF) (Global Hectares per Capita)				
	1.720024	0.3316092	−0.0822707	2.875039
Environmental Policy Stringency (EPS) (0–100)				
	4.023328	0.2023284	3.396999	4.402329
Total Natural Resourc Rent (TNR)				
	0.727	1.427	−6.2445	3.256

4.2. Diagnostic Test Results

The empirical analysis in the current study begins with an examination of the panel's cross-sectional dependency. According to Chudik and Pesaran [86], if the CSD issue is ignored, long-term coefficient estimations and stationarity may become skewed and inconsistent. The results are shown in Table 3. Countries and economies are connected to one another in the globalizing globe via financial integration and trade agreements. These countries are connected on economic, social, and financial levels. This prompts us to investigate the CSD. At the 1% level, it was shown that every test has the highest level of significance. This implies that the series contains CSD. A considerable cross-sectional dependency is indicated by the findings of all CSD tests for the panel's variables and models.

After CSD, slope coefficients are predicted to differ among cross-sectional units; hence, slope heterogeneity should be examined. Neglecting slope heterogeneity concerns might lead to estimates that are skewed and inconsistent. This analysis shows that macroeconomic aggregates, including income levels, energy consumption, renewable energy structures, etc., vary significantly among the G-20 nations, despite their inherent connections. It is impossible to disagree with slope heterogeneity issues in this regard. This is why the slope heterogeneity test of Pesaran and Yamagata [65] was used in this research. Using this approach, two test statistics (De and Deadj) are estimated with the assumption that the slopes of all cross-sectional units are homogeneous. Slope heterogeneity is verified by the statistics of the De and Deadj tests. Additionally, the panel's results are indicative of heteroscedasticity. Taking into account the challenges with CSD and slope heterogeneity,

the most appropriate unit root, cointegration, long-run coefficient estimate, and causality techniques are selected.

Table 3. Diagnostic test results.

Problem	Test	Test. Stat.	Prob.
Cross S.D	Breusch and Pagan LM	1327 ***	0.000
	Pesaran LM adj	8.9 ***	0.000
	Pesaran CD	5.094 ***	0.000
Slope Heterogeneity	Δ	21.966 ***	0.000
	Δ^ adj	26.400 ***	0.000
Heteroscedasticity	Breusch–Pagan/Cook–Weisberg	3.66 ***	0.003

Note: *** significant at 1%.

4.3. Cross-Sectional Dependence Test Results

To estimate accurate and reliable coefficients and prevent misleading regression, all variables must have their stationarity checked (second generation) following tests for slope heterogeneity and CSD in the dataset. The CIPS test is employed to determine the unit root, since all the variables in Table 3 demonstrate slope heterogeneity and cross-sectional dependency according to the CSD test findings. Both CSD and slope heterogeneity can be applied to this test. The CIPS test results for the dataset are shown in Table 4. The series is nonstationary, and the hypothesis under investigation (H_0) pertains to whether the series contains a unit root. The data indicate that the variables exhibit non-stationarity at the I (0) level for both trend and intercept, and I (1) stationary behavior for first-order differences. This indicates that none of the variables have a unit root issue.

Table 4. CIPS test results.

Variables	
At level (Intercept and Trend)	
lnEF	−2.466
lnIG	−2.998 ***
lnTNR	−3.870 ***
lnUR	−2.051
lnFI	−2.164
lnEPS	−4.010 ***
lnGI	−2.330
At first difference (only with intercept)	
lnEF	−4.047 ***
lnIG	−3.787 ***
lnTNR	−5.726 ***
lnUR	−3.775 ***
lnFI	−4.504 ***
lnEPS	−5.705 ***
lnGI	−3.251 ***

*** Significant at 1%.

4.4. Co Integration Test Results

Table 5 illustrates the empirical highlights of Westerlund's test results, which imply there is long-term cointegration between the variables such as inclusive growth, total natural resource rent, urbanization, fintech index, environmental policy stringency, globalization and ecological footprint. The null hypothesis is that there is no cointegration, whereas the alternative hypothesis is that there is cointegration. The null hypothesis that

there is no cointegration is significantly rejected by the statistically significant panel-*t*-test statistics (2.3670) and Prob (0.0090).

Table 5. Westerlund cointegration result.

Panel	Variance Ratio	
	Statis.	**Prob.**
	−2.3670 ***	0.0090

*** shows a significance level at 1%.

4.5. Regression Analysis

Table 6 shows regression findings using the Driscoll–Kraay standard error (D/K) and Generalized Methods of Moments (GMMs) approach. The *p*-value for the coefficient of 0.008 is 0.380, and its D/K standard error is 0.010. The implication is that inclusive growth has no effect on ecological footprint. The *p*-value for the coefficient of 0.292 is 0.000, and its D/K standard error is 0.027. This implies that ecological footprint and natural resource rent have a statistically significant negative relationship. The D/K standard error for the coefficient of 0.575 is 0.075 and 0.000 is the *p*-value. This implies a robust positive correlation between the ecological footprint and urbanization. The *p*-value for the coefficient of 0.434 is 0.000, and its D/K standard error is 0.028. This suggests that the fintech index and ecological footprint have a statistically significant negative association. The *p*-value for the coefficient of 0.081 is 0.000, and its D/K standard error is 0.008. This implies that there is a statistically significant and negative correlation between the stringency of environmental policies and ecological footprint. The *p*-value for the 0.095 coefficient is 0.000, and its D/K standard error is 0.005. This implies that the ecological footprint and globalization have a statistically significant negative association. All the variables, with the exception of inclusive growth, are significant at the 1% level.

Table 6. Results of regression estimation.

Variables	D/K			GMM		
	Coff.	**Std. Err.**	**Prob.**	**Coff.**	**Std. Err.**	**Prob.**
lnIG	−0.008	0.010	0.380	−0.022 ***	0.006	0.003
lnTNR	−0.292 ***	0.027	0.000	−0.043 **	0.019	0.038
lnUR	0.575 ***	0.075	0.000	1.070 ***	0.053	0.000
lnFI	−0.434 ***	0.028	0.000	−0.238 **	0.037	0.015
lnEPS	−0.081 ***	0.008	0.000	−0.130 ***	0.003	0.000
lnGI	−0.095 ***	0.005	0.000	−0.108 ***	0.108	0.000

** Significant at 5% and *** Significant at 1%.

The *p*-value for the coefficient of 0.022 is 0.003, and its GMM standard error is 0.006. This suggests that inclusive growth and ecological impact are negatively correlated in a statistically meaningful way. The *p*-value for the coefficient of 0.043 is 0.038, and its GMM standard error is 0.019. This suggests that ecological footprint and natural resource rent have a statistically significant negative connection. The GMM standard error for the coefficient of 1.070 is 0.053 and 0.000 is the *p*-value. This implies that urbanization and ecological footprint have a very significant positive relationship. The *p*-value for the coefficient of 0.238 is 0.015, and the GMM standard error is 0.037. Based on statistical analysis, there is a considerable negative correlation between the fintech index and ecological footprint. The *p*-value for the coefficient of 0.130 is 0.000, and its GMM standard error is 0.003. This implies that the ecological footprint and the strictness of environmental regulations have a negative

and statistically significant connection. The GMM standard error for the coefficient of 0.108 is 0.108, and the *p*-value is 0.000. This suggests that the association between ecological footprint and globalization is statistically significant and detrimental. All these variables exhibit significance at the 1% level, except for fintech index and natural resource rent, which exhibit significance at the 5% level.

Table 7 depicts regression results by employing the PCSEs approach. The *p*-value for the coefficient of IG is 0.000. The proposition is that IG has a negative impact on ecological footprint. The *p*-value for the coefficient of TNR is 0.036 and its standard error is 0.089. This suggests that ecological footprint and TNR have a statistically significant negative correlation. The standard error for the coefficient of UR is 0.007 and 0.000 is the *p*-value. This means that there is a strong positive association linking the ecological footprint and UR. The *p*-value for the coefficient of FI is 0.046, and its standard error is 0.098. This implies that the FI and ecological footprint have a statistically significant negative relationship. The *p*-value for the coefficient of EPS is 0.002, and its standard error is 0.019. This shows that there is a statistically significant and negative link between the EPS and ecological footprint. The *p*-value for the GI coefficient is 0.000, and its standard error is 0.006. This suggests that the ecological footprint and GI have a statistically significant declining association. Variables such as IG, UR, EPS and GI are significant at the 1% level; however, TNR and FI are significant at the 5% level.

Table 7. Results of Prais–Winsten regression; correlated panel-corrected standard errors (PCSEs).

Variables	Coff.	Std. Err.	Prob.
lnIG	−0.023 ***	6.06×10^{-6}	0.000
lnTNR	−0.055 **	0.089	0.036
lnUR	0.027 ***	0.007	0.000
lnFI	−0.719 **	0.098	0.046
lnEPS	−0.020 ***	0.019	0.002
lnGI	−0.022 ***	0.006	0.000

** Significant at 5% and *** significant at 1%.

4.6. Causality Test Results

Table 8 presents the findings from the paired Juodis, Karavias, and Sarafidis causality test. The findings demonstrate a bidirectional causal relationship between IG and EF, UR and EF, FI and EF, EPS and EF, GI and EF and a unidirectional relationship between TNR and EF.

Table 8. Pairwise Juodis, Karavias, and Sarafidis (2021) test results.

				G-20		
1	IG ≠ EF	26.525 ***	0.000	−0.132 ***	0.000	Bidirectional
2	EF ≠ IG	6.432 **	0.011	−0.028 **	0.011	
3	TNR ≠ EF	40.147 ***	0.000	0.193 ***	0.000	Unidirectional
4	EF ≠ TNR	0.603	0.437	0.009	0.437	
5	UR ≠ EF	11.685 ***	0.001	−0.070 ***	0.001	Bidirectional
6	EF ≠ UR	24.413 ***	0.000	0.098 ***	0.000	
7	FI ≠ EF	9.801 ***	0.001	−0.002 ***	0.002	Bidirectional
8	EF ≠ FI	3.766	0.052	0.941 *	0.052	
9	EPS ≠ EF	5.314 **	0.021	−0.011 **	0.021	Bidirectional
10	EF ≠ EPS	28.407 ***	0.000	−0.296 ***	0.000	
11	GI ≠ EF	8.622 ***	0.003	0.0402 ***	0.003	Bidirectional
12	EF ≠ GI	21.624 ***	0.000	0.177 ***	0.000	

*** Significant at 1%; ** significant at 5%; * significant at 10%.

5. Discussion

The findings indicate that a rise in inclusive growth reduces ecological impact. The results align with the findings of Bennett, Villasante [46]. This is because while inclusive growth initially results in more environmental deterioration, it eventually improves environmental conditions. The negative coefficient of inclusive growth implies that improved environmental regulations, innovation, and structural adjustments to the economy might lessen environmental issues once a particular income level is reached. Ulucak and Bilgili [87] argue that because of strict environmental laws and technical advancements brought about by research and development, high income levels may lessen the ecological footprint in industrialized nations. The finding suggests that ecological footprint is negatively impacted by natural resource rent. This finding is in line with earlier research by Erdoğan, Çakar [88]. The primary rationale should be that as natural resource rent rises, so do the costs associated with its development and use. This leads to more stringent environmental regulations, which in turn cause natural resource rent to decline along with its use and ecological footprint. Furthermore, by killing species, contaminating the air, water, and land masses, causing land instability, deforestation, and global warming, the exploitation, exploration, mining, and processing of natural resources harm the environment [89]. Natural resources could improve sustainability by reducing environmental deterioration brought on by climate change.

Urbanization also increases ecological impact. Urbanization adds to environmental damage, waste production, and deforestation in addition to decreasing agricultural output by expanding urban regions [90,91]. It has been demonstrated that urbanization, which is characterized by an increase in infrastructure and modifications to land use, has a negative impact on the environment. These consequences comprise habitat degradation, biodiversity loss, and disturbances in the delivery of ecosystem services. Additionally, the concentration of industry and transportation infrastructure in cities tends to raise the pollution levels in the air and water. The growing urban areas put more strain on the limited natural resource rent due to the rising demand for electricity, water, and building materials. This means that to mitigate environmental degradation in G-20 countries, sustainable urban planning and resource management policies must be put into place due to the negative effects of urbanization on the ecological footprint. These findings support the research conducted by Yasmeen, Tan [48] and Khan, Hou [49].

The findings show that the ecological footprint is significantly and negatively impacted by the fintech index. According to these results, fintech may significantly increase the availability of environmentally friendly investments in G-20 nations. This is made possible by the strategic use of blockchain technology and big data insights, which encourage eco-friendly change among enterprises and potential investors alike. As a result, these developments support a more environmentally conscious and sustainable financial environment by reducing environmental footprints. Furthermore, integrating fintech into the banking and finance industry contributes to increasing environmental effectiveness and drastically lessens the reliance on the conventional energy-intensive banking IT industry. Similar results were also reported by Qin, Aziz [92] and Udeagha and Muchapondwa [93].

The ecological footprint decreases with increased environmental policy stringency. Policy initiatives in the nations that estimate significant emissions to lessen the impact of pollution are useful for gauging the level of stringency with which these nations have committed themselves. Several factors, including policy structure, promoted technology, and the overall political and economic climate, will affect how well strict environmental regulations reduce greenhouse gas emissions throughout the energy transformation. Energy efficiency, renewable energy, and emissions reduction are examples of green energy activities that are commonly promoted by environmental legislation and incentives [94]. Such regulations are motivating, achievable, and instantly enforceable, yet can help change industrial and public behavior in the direction of sustainable economies and environments. These findings align with previous research conducted by Sadik-Zada and Ferrari [53]; Afshan, Ozturk [54]; Wang, Yen-Ku [57]; Yirong [58].

Globalization via commerce also facilitates increasing economic activity and technological improvement, which is why there is a negative association between globalization and ecological impact. The extraction and utilization of natural resources are under strain due to the dramatic increase in modern societies' consumption needs, which is a result of both high levels of wealth and population growth. According to optimists, globalization is a process that raises economic growth and per capita income, which in turn raises money for sustainable development and solves environmental issues across the globe [95]. The research by Rjoub, Odugbesan [51] for Sweden and Koengkan, Fuinhas [52] for Latin America confirmed the negative association between environmental degradation and globalization.

6. Conclusions

The results of the regression analysis with Driscoll–Kraay standard errors (D/K) and Generalized Method of Moments (GMMs) have followed the very detailed insights of the factors affecting the ecological footprint across the G-20 countries. According to the analysis, inclusive growth has minimal impact under D/K and its impact is starkly contrasted with GMM results. Inclusive growth could initially lead to environmental harm but overall should lead to an ecological improvement. Natural resource rent is always strongly inversely linked with the ecological footprint, meaning that the stricter rules and higher costs of removing the resources will mitigate the degradation. On the contrary, urbanization correlates positively with the ecological footprint, posing environmental challenges related to urban sprawl and infrastructure development.

More interesting is the strong and inverse relationship between the fintech index and the ecological footprint, which states that financial technology can boost green investment and can be useful for reducing its environmental impact. Equally, severe environmental policies and globalization present a negative effect in relations to the ecological footprint, reinforcing the essentiality of implementing strict regulations and open trade to limit environmental damage. This is based on causality tests conducted by Juodis, Karavias, and Sarafidis, and it gives a clear affirmation that there is a bidirectional relationship amid

inclusive growth, urbanization, fintech index, environmental policy stringency, and globalization with the ecological footprint. Meanwhile, natural resource rent has a unidirectional relationship with the ecological footprint.

These findings greatly underscore the need for strong plausible policy measures focused on urban planning and fintech adoption, particularly for the G-20 countries, which will allow them to manage their ecological impacts and encourage them to adopt environmentally conscious practices.

7. Policy Implications

Policymakers need to ensure inclusive economic growth that incorporates environmentally sustainable practices. These practices could include incentives for businesses that use green technologies, education and training of workers to prepare for the transition to green jobs, and rules that mandate more renewable sources of energy.

On the other hand, this relationship may stand to indicate that with strict regulatory regimes and responsible management practices, environmental degradation can be reduced. This means governments should apply strict environmental standards in resource extraction and further diversify economies to minimize dependency on resource rents. Urbanization increases the ecological impact of habitat degradation, pollution, and heavy resource consumption. A sustainable urban planning approach might include greener mass transit options, mass transit enhancement, or financial incentives that would encourage green building practices to reduce the environmental impact of building new infrastructure.

The negative relationship between the fintech index and its ecological footprint suggests that financial technology is driving eco-friendly investments. It is recommended that governments and financial institutions support fintech solutions that allow sustainable investments with better transparency, which may involve using blockchain technology and leveraging big data to help identify and manage ecological risks. This is a policy under which the ecological footprint can be significantly reduced by the presence of stricter environmental policies. The policy should lay out strict guidelines, which very clearly indicate the permissible level of emissions, strictly enforce pollution controls, and encourage the production of cleaner varieties. To achieve this objective, it is quite necessary to ensure international cooperation via experience exchanges and to develop unified criteria for controlling respective activities. The character of the negative correlation between globalization and ecological footprints calls for sustainable trade. Trade should be encouraged by trade agreements to engage in environmentally friendly production and allow for the transfer of green technologies and practices by removing obstacles that hinder the acceptance of sustainable products.

Any concentration or necessary attention by the G-20 should be paid towards economic complexity and industrial diversification. Significant attention should be paid to using technology and knowledge-intensive methods of production that provide opportunities which may increase productivity, encourage innovation, and ensure that products and services are of high value. Governments should provide an incentive to industries which support the greener economies and, hence, have reduced dependence on finite resources. These strategies will support sustainable practice and, at the same time, strengthen global competitiveness and the economic stability of G-20 nations. Implementing proactive measures now will help establish a healthier planet for the future.

8. Research Limitations

Scope of Policies: Above all, this study is focused on macro-level policies (e.g., G-20 initiatives, international cooperation) and does not delve into micro-level practices or country differences in policy implementations.

Limited Geographic Representation: While relevant to all nations, the recommendations are disproportionately linked to industrial and emerging economies, leaving a knowledge gap regarding the concerns of low-income nations.

Technological Assumptions: The scalability, accessibility, and user adoption of proposed fintech solutions and green technologies can differ drastically across regions and will determine their effectiveness.

Economic Diversification Challenges: Moving economies away from their dependence on resource revenue is easier said than done, as it takes long-term planning, heavy investments, and political willingness—all of which are often absent.

9. Future Prospects

Advancements in Green Technologies: The transition to greener economies may be accelerated because it would encourage future research and innovation in the area of renewable energy, eco-friendly materials, and sustainable urban development.

Integration of Fintech and Environmental Goals: The potential for leveraging financial technology to increase transparency, facilitate eco-conscious investments and manage ecological risks is massive. How governments and institutions are currently monitoring and mitigating environmental impacts can be revolutionized with blockchain and big data analytics.

International Cooperation: Global ecological challenges can be addressed by a set of unified international guidelines for emissions, sustainable trade agreements and technology transfer. Greater cooperation among G-20 nations will create a global benchmark for sustainable practices.

Urban Sustainability Innovations: Adoption of smart cities, green mass transit, and eco-friendly construction of infrastructure will sharply decrease the ecological footprint of urbanization.

Economic Diversification Strategies: Knowledge-intensive and technology-driven industries will be offered avenues for diversifying economies away from over-reliance on unsustainable heavy industry and for launching economic growth.

Education and Public Awareness: We can increase awareness and training programs for green jobs so that the workforce is ready for the sustainable transition, with inclusive economic and ecological benefits.

Policy Development and Enforcement: More stringent enforcement of environmental policies (emission limits and penalties for violation) is critical. These policies can be analyzed for their effectiveness in various geopolitical settings in future research.

Longitudinal Studies: Further longitudinal studies can provide further insights into the long-term impacts of proposed policies and practices, and researchers will ultimately be able to refine or adapt them accordingly.

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References

1. Dong, K.; Dong, X.; Dong, C. Determinants of the global and regional CO_2 emissions: What causes what and where? *Appl. Econ.* **2019**, *51*, 5031–5044. [CrossRef]
2. Khan, S.A.R.; Sharif, A.; Golpîra, H.; Kumar, A. A green ideology in Asian emerging economies: From environmental policy and sustainable development. *Sustain. Dev.* **2019**, *27*, 1063–1075. [CrossRef]
3. Zhang, J.; Yasin, I. Greening the BRICS: How Green Innovation Mitigates Ecological Footprints in Energy-Hungry Economies. *Sustainability* **2024**, *16*, 3980. [CrossRef]

4. Ritchie, H.; Roser, M.; Rosado, P. CO_2 and greenhouse gas emissions. In *Our World Data*; Oxford University Press: Oxford, UK, 2023.
5. Lindsey, L.L. *Gender: Sociological Perspectives*; Routledge: London, UK, 2020.
6. Haines, A.; Patz, J.A. Health effects of climate change. *JAMA* **2004**, *291*, 99–103. [CrossRef]
7. Aluko, O.A.; Opoku, E.E.O.; Ibrahim, M. Investigating the environmental effect of globalization: Insights from selected industrialized countries. *J. Environ. Manag.* **2021**, *281*, 111892. [CrossRef] [PubMed]
8. Acemoglu, D.; Rafey, W. Mirage on the horizon: Geoengineering and carbon taxation without commitment. *J. Public Econ.* **2023**, *219*, 104802. [CrossRef]
9. Greenstone, M.; He, G.; Li, S.; Zou, E.Y. China's war on pollution: Evidence from the first 5 years. *Rev. Environ. Econ. Policy* **2021**, *15*, 281–299. [CrossRef]
10. Böhringer, C.; Carbone, J.C.; Rutherford, T.F. Unilateral climate policy design: Efficiency and equity implications of alternative instruments to reduce carbon leakage. *Energy Econ.* **2012**, *34*, S208–S217. [CrossRef]
11. Hepburn, C.; Pless, J.; Popp, D. Policy brief—Encouraging innovation that protects environmental systems: Five policy proposals. *Rev. Environ. Econ. Policy* **2018**, *12*, 1–26. [CrossRef]
12. Tietenberg, T.; Lewis, L. *Environmental and Natural Resource Economics*; Routledge: London, UK, 2018.
13. Kamah, M.; Riti, J.S.; Bin, P. Inclusive growth and environmental sustainability: The role of institutional quality in sub-Saharan Africa. *Environ. Sci. Pollut. Res.* **2021**, *28*, 34885–34901. [CrossRef] [PubMed]
14. Xu, J.; Chen, F.; Zhang, W.; Liu, Y.; Li, T. Analysis of the carbon emission reduction effect of Fintech and the transmission channel of green finance. *Financ. Res. Lett.* **2023**, *56*, 104127. [CrossRef]
15. Feng, H.; Li, Y. The role of fintech, natural resources, environmental taxes and urbanization on environmental sustainability: Evidence from the novel panel data approaches. *Resour. Policy* **2024**, *92*, 104970. [CrossRef]
16. Chang, Y.; Wu, P. Influence of fiscal decentralization, fintech, and mineral resources on green productivity of G5 countries. *Resour. Policy* **2024**, *89*, 104509. [CrossRef]
17. Lu, Y.; Tian, T.; Ge, C. Asymmetric effects of renewable energy, fintech development, natural resources, and environmental regulations on the climate change in the post-covid era. *Resour. Policy* **2023**, *85*, 103902. [CrossRef]
18. Firdousi, S.F.; Afzal, A.; Amir, B. Nexus between FinTech, renewable energy resource consumption, and carbon emissions. *Environ. Sci. Pollut. Res.* **2023**, *30*, 84686–84704. [CrossRef]
19. Lee, C.-C.; Ni, W.; Zhang, X. FinTech development and commercial bank efficiency in China. *Glob. Financ. J.* **2023**, *57*, 100850. [CrossRef]
20. Dreher, A.; Gaston, N.; Martens, P. *Measuring Globalisation: Gauging Its Consequences*; Springer: New York, NY, USA, 2008.
21. Jones, A. *Globalization: Key Thinkers*; Polity: Cambridge, UK, 2010; Volume 1.
22. Rennen, W.; Martens, P. The globalisation timeline. *Integr. Assess.* **2003**, *4*, 137–144. [CrossRef]
23. Figge, L.; Oebels, K.; Offermans, A. The effects of globalization on Ecological Footprints: An empirical analysis. *Environ. Dev. Sustain.* **2017**, *19*, 863–876. [CrossRef]
24. Martens, P.; Rotmans, J. Transitions in a globalising world. *Futures* **2005**, *37*, 1133–1144. [CrossRef]
25. Hoekstra, A.Y.; Wiedmann, T.O. Humanity's unsustainable environmental footprint. *Science* **2014**, *344*, 1114–1117. [CrossRef] [PubMed]
26. Xue, C.; Shahbaz, M.; Ahmed, Z.; Ahmad, M.; Sinha, A. Clean energy consumption, economic growth, and environmental sustainability: What is the role of economic policy uncertainty? *Renew. Energy* **2022**, *184*, 899–907. [CrossRef]
27. Pham, T.H.A.; Lin, C.-Y.; Moslehpour, M.; Van Vo, T.T.; Nguyen, H.-T.; Nguyen, T.T.H. What role financial development and resource-curse situation play in inclusive growth of Asian countries. *Resour. Policy* **2024**, *88*, 104498. [CrossRef]
28. He, B.; Jie, W.; He, H.; Alsubih, M.; Arnone, G.; Makhmudov, S. From resources to resilience: How green innovation, fintech and natural resources shape sustainability in OECD countries. *Resour. Policy* **2024**, *91*, 104856. [CrossRef]
29. Feng, S.; Chong, Y.; Yu, H.; Ye, X.; Li, G. Digital financial development and ecological footprint: Evidence from green-biased technology innovation and environmental inclusion. *J. Clean. Prod.* **2022**, *380*, 135069. [CrossRef]
30. Lisha, L.; Mousa, S.; Arnone, G.; Muda, I.; Huerta-Soto, R.; Shiming, Z. Natural resources, green innovation, fintech, and sustainability: A fresh insight from BRICS. *Resour. Policy* **2023**, *80*, 103119. [CrossRef]
31. Xia, A.; Liu, Q. Modelling the asymmetric impact of fintech, natural resources, and environmental regulations on ecological footprint in G7 countries. *Resour. Policy* **2024**, *89*, 104552. [CrossRef]
32. Ali, M.; Joof, F.; Samour, A.; Tursoy, T.; Balsalobre-Lorente, D.; Radulescu, M. Testing the impacts of renewable energy, natural resources rent, and technological innovation on the ecological footprint in the USA: Evidence from Bootstrapping ARDL. *Resour. Policy* **2023**, *86*, 104139. [CrossRef]
33. Shu, X.; Usman, M.; Ahmad, P.; Irfan, M. Analyzing the asymmetric FinTech services under natural resources, and renewable energy in the future environmental performance: New insights from STIRPAT model framework. *Resour. Policy* **2024**, *92*, 104984. [CrossRef]

34. Tahir, T.; Luni, T.; Majeed, M.T.; Zafar, A. The impact of financial development and globalization on environmental quality: Evidence from South Asian economies. *Environ. Sci. Pollut. Res.* **2021**, *28*, 8088–8101. [CrossRef] [PubMed]
35. Duttagupta, R.; Lizarazo Ruiz, S.; Martinez Leyva, A.; Mendes Tavares, M. Globalization and inclusive growth: Can they go hand in hand in developing countries? In *Getting Globalization Right: Sustainability and Inclusive Growth in the Post Brexit Age*; Springer: Berlin/Heidelberg, Germany, 2019; pp. 265–288.
36. Ehrlich, P.R.; Holdren, J.P. Impact of Population Growth: Complacency concerning this component of man's predicament is unjustified and counterproductive. *Science* **1971**, *171*, 1212–1217. [CrossRef] [PubMed]
37. Raskin, P.D. Methods for estimating the population contribution to environmental change. *Ecol. Econ.* **1995**, *15*, 225–233. [CrossRef]
38. York, R.; Rosa, E.A.; Dietz, T. Footprints on the earth: The environmental consequences of modernity. *Am. Sociol. Rev.* **2003**, *68*, 279–300. [CrossRef]
39. Yasin, I.; Naseem, S.; Anwar, M.A.; Madni, G.R.; Mahmood, H.; Murshed, M. An analysis of the environmental impacts of ethnic diversity, financial development, economic growth, urbanization, and energy consumption: Fresh evidence from less-developed countries. *Environ. Sci. Pollut. Res.* **2022**, *29*, 79306–79319. [CrossRef]
40. Yasin, I.; Ahmad, N.; Amin, S.; Sattar, N.; Hashmat, A. Does agriculture, forests, and energy consumption foster the carbon emissions and ecological footprint? fresh evidence from BRICS economies. *Environ. Dev. Sustain.* **2024**, *26*, 1–21. [CrossRef]
41. Dietz, T.; Rosa, E.A. Rethinking the environmental impacts of population, affluence and technology. *Hum. Ecol. Rev.* **1994**, *1*, 277–300.
42. Gygli, S.; Haelg, F.; Potrafke, N.; Sturm, J.-E. The KOF globalisation index–revisited. *Rev. Int. Organ.* **2019**, *14*, 543–574. [CrossRef]
43. Xu, S.; Zhang, Y.; Chen, L.; Leong, L.W.; Muda, I.; Ali, A. How Fintech and effective governance derive the greener energy transition: Evidence from panel-corrected standard errors approach. *Energy Econ.* **2023**, *125*, 106881. [CrossRef]
44. Tan, Q.; Yasmeen, H.; Ali, S.; Ismail, H.; Zameer, H. Fintech development, renewable energy consumption, government effectiveness and management of natural resources along the belt and road countries. *Resour. Policy* **2023**, *80*, 103251. [CrossRef]
45. Emara, N. Asymmetric and threshold effects of FinTech on poverty in SSA countries. *J. Econ. Stud.* **2022**, *50*, 921–946. [CrossRef]
46. Bennett, N.J.; Villasante, S.; Espinosa-Romero, M.J.; Lopes, P.F.; Selim, S.A.; Allison, E.H. Social sustainability and equity in the blue economy. *One Earth* **2022**, *5*, 964–968. [CrossRef]
47. Geng, B.; Wu, D.; Zhang, C.; Xie, W.; Mahmood, M.A.; Ali, Q. How Can the Blue Economy Contribute to Inclusive Growth and Ecosystem Resources in Asia? A Comparative Analysis. *Sustainability* **2024**, *16*, 429. [CrossRef]
48. Yasmeen, H.; Tan, Q.; Zameer, H.; Tan, J.; Nawaz, K. Exploring the impact of technological innovation, environmental regulations and urbanization on ecological efficiency of China in the context of COP21. *J. Environ. Manag.* **2020**, *274*, 111210. [CrossRef]
49. Khan, I.; Hou, F.; Le, H.P.; Ali, S.A. Do natural resources, urbanization, and value-adding manufacturing affect environmental quality? Evidence from the top ten manufacturing countries. *Resour. Policy* **2021**, *72*, 102109. [CrossRef]
50. Ahmad, M.; Pata, U.K.; Ahmed, Z.; Zhao, R. Fintech, natural resources management, green energy transition, and ecological footprint: Empirical insights from EU countries. *Resour. Policy* **2024**, *92*, 104972. [CrossRef]
51. Rjoub, H.; Odugbesan, J.A.; Adebayo, T.S.; Wong, W.-K. Sustainability of the moderating role of financial development in the determinants of environmental degradation: Evidence from Turkey. *Sustainability* **2021**, *13*, 1844. [CrossRef]
52. Koengkan, M.; Fuinhas, J.A.; Santiago, R. Asymmetric impacts of globalisation on CO_2 emissions of countries in Latin America and the Caribbean. *Environ. Syst. Decis.* **2020**, *40*, 135–147. [CrossRef]
53. Sadik-Zada, E.R.; Ferrari, M. Environmental policy stringency, technical progress and pollution haven hypothesis. *Sustainability* **2020**, *12*, 3880. [CrossRef]
54. Afshan, S.; Ozturk, I.; Yaqoob, T. Facilitating renewable energy transition, ecological innovations and stringent environmental policies to improve ecological sustainability: Evidence from MM-QR method. *Renew. Energy* **2022**, *196*, 151–160. [CrossRef]
55. Li, K.; Qi, S.; Shi, X. The COVID-19 pandemic and energy transitions: Evidence from low-carbon power generation in China. *J. Clean. Prod.* **2022**, *368*, 132994. [CrossRef]
56. Li, Z.; Kuo, Y.-K.; Mahmud, A.R.; Nassani, A.A.; Haffar, M.; Muda, I. Integration of renewable energy, environmental policy stringency, and climate technologies in realizing environmental sustainability: Evidence from OECD countries. *Renew. Energy* **2022**, *196*, 1376–1384. [CrossRef]
57. Wang, Z.; Yen-Ku, K.; Li, Z.; An, N.B.; Abdul-Samad, Z. The transition of renewable energy and ecological sustainability through environmental policy stringency: Estimations from advance panel estimators. *Renew. Energy* **2022**, *188*, 70–80. [CrossRef]
58. Yirong, Q. Does environmental policy stringency reduce CO2 emissions? Evidence from high-polluted economies. *J. Clean. Prod.* **2022**, *341*, 130648. [CrossRef]
59. Jie, H.; Khan, I.; Alharthi, M.; Zafar, M.W.; Saeed, A. Sustainable energy policy, socio-economic development, and ecological footprint: The economic significance of natural resources, population growth, and industrial development. *Util. Policy* **2023**, *81*, 101490. [CrossRef]

60. Wang, Y.; Liu, J.; Zhao, Z.; Ren, J.; Chen, X. Research on carbon emission reduction effect of China's regional digital trade under the "double carbon" target--combination of the regulatory role of industrial agglomeration and carbon emissions trading mechanism. *J. Clean. Prod.* **2023**, *405*, 137049. [CrossRef]
61. Sohail, M.T.; Ullah, S.; Majeed, M.T. Effect of policy uncertainty on green growth in high-polluting economies. *J. Clean. Prod.* **2022**, *380*, 135043. [CrossRef]
62. Pesaran, M.H. General diagnostic tests for cross section dependence in panels. Cambridge Working Papers. *Economics* **2004**, *1240*, 1.
63. Breusch, T.S.; Pagan, A.R. The Lagrange multiplier test and its applications to model specification in econometrics. *Rev. Econ. Stud.* **1980**, *47*, 239–253. [CrossRef]
64. Swamy, P.A. Efficient inference in a random coefficient regression model. *Econom. J. Econom. Soc.* **1970**, *38*, 311–323. [CrossRef]
65. Pesaran, M.H.; Yamagata, T. Testing slope homogeneity in large panels. *J. Econom.* **2008**, *142*, 50–93. [CrossRef]
66. Ilori, O.O.; Tanimowo, F.O. Heteroscedasticity Detection in Cross-Sectional Diabetes Pedigree Function: A Comparison of Breusch-Pagan-Godfrey, Harvey and Glejser Tests. *Int. J. Sci. Manag. Res.* **2022**, *5*, 150–163. [CrossRef]
67. Wiedermann, W.; Artner, R.; von Eye, A. Heteroscedasticity as a basis of direction dependence in reversible linear regression models. *Multivar. Behav. Res.* **2017**, *52*, 222–241. [CrossRef] [PubMed]
68. Im, K.S.; Pesaran, M.H.; Shin, Y. Testing for unit roots in heterogeneous panels. *J. Econom.* **2003**, *115*, 53–74. [CrossRef]
69. Levin, A.; Lin, C.-F.; Chu, C.-S.J. Unit root tests in panel data: Asymptotic and finite-sample properties. *J. Econom.* **2002**, *108*, 1–24. [CrossRef]
70. Breitung, J. The local power of some unit root tests for panel data. In *Nonstationary Panels, Panel Cointegration, and Dynamic Panels*; Emerald Group Publishing Limited: Bingley, UK, 2001; pp. 161–177.
71. Pesaran, M.H. A simple panel unit root test in the presence of cross-section dependence. *J. Appl. Econom.* **2007**, *22*, 265–312. [CrossRef]
72. Pesaran, M.H. Testing weak cross-sectional dependence in large panels. *Econom. Rev.* **2015**, *34*, 1089–1117. [CrossRef]
73. Sulich, A.; Sołoducho-Pelc, L. The circular economy and the Green Jobs creation. *Environ. Sci. Pollut. Res.* **2022**, *29*, 14231–14247. [CrossRef]
74. Westerlund, J. Testing for error correction in panel data. *Oxf. Bull. Econ. Stat.* **2007**, *69*, 709–748. [CrossRef]
75. Persyn, D.; Westerlund, J. Error-correction–based cointegration tests for panel data. *Stata J.* **2008**, *8*, 232–241. [CrossRef]
76. Ullah, S.; Akhtar, P.; Zaefarian, G. Dealing with endogeneity bias: The generalized method of moments (GMM) for panel data. *Ind. Mark. Manag.* **2018**, *71*, 69–78. [CrossRef]
77. Berk, I.; Kasman, A.; Kılınç, D. Towards a common renewable future: The System-GMM approach to assess the convergence in renewable energy consumption of EU countries. *Energy Econ.* **2020**, *87*, 103922. [CrossRef]
78. Arellano, M.; Bond, S. Some tests of specification for panel data: Monte Carlo evidence and an application to employment equations. *Rev. Econ. Stud.* **1991**, *58*, 277–297. [CrossRef]
79. Blundell, R.; Bond, S. Initial conditions and moment restrictions in dynamic panel data models. *J. Econom.* **1998**, *87*, 115–143. [CrossRef]
80. Roodman, D. How to do xtabond2: An introduction to difference and system GMM in Stata. *Stata J.* **2009**, *9*, 86–136. [CrossRef]
81. Choi, J. Econometric estimation of the climate change policy effect in the US transportation sector. *J. Clim. Chang. Res.* **2017**, *8*, 1–10. [CrossRef]
82. Arellano, M.; Bover, O. Another look at the instrumental variable estimation of error-components models. *J. Econom.* **1995**, *68*, 29–51. [CrossRef]
83. Beck, N.; Katz, J.N. What to do (and not to do) with time-series cross-section data. *Am. Political Sci. Rev.* **1995**, *89*, 634–647. [CrossRef]
84. Xiao, J.; Karavias, Y.; Juodis, A.; Sarafidis, V.; Ditzen, J. Improved tests for Granger noncausality in panel data. *Stata J.* **2023**, *23*, 230–242. [CrossRef]
85. Juodis, A.; Karavias, Y.; Sarafidis, V. A homogeneous approach to testing for Granger non-causality in heterogeneous panels. *Empir. Econ.* **2021**, *60*, 93–112. [CrossRef]
86. Chudik, A.; Pesaran, M.H. Large panel data models with cross-sectional dependence: A survey. In *The Oxford Handbook of Panel Data*; Oxford University Press: Oxford, UK, 2015.
87. Ulucak, R.; Bilgili, F. A reinvestigation of EKC model by ecological footprint measurement for high, middle and low income countries. *J. Clean. Prod.* **2018**, *188*, 144–157. [CrossRef]
88. Erdoğan, S.; Çakar, N.D.; Ulucak, R.; Danish; Kassouri, Y. The role of natural resources abundance and dependence in achieving environmental sustainability: Evidence from resource-based economies. *Sustain. Dev.* **2021**, *29*, 143–154. [CrossRef]
89. Zakari, A.; Khan, I. The introduction of green finance: A curse or a benefit to environmental sustainability? *Energy Res. Lett.* **2022**, *3*, 1–5. [CrossRef]

90. Ahmed, Z.; Zafar, M.W.; Ali, S. Linking urbanization, human capital, and the ecological footprint in G7 countries: An empirical analysis. *Sustain. Cities Soc.* **2020**, *55*, 102064. [CrossRef]
91. Ali, R.; Bakhsh, K.; Yasin, M.A. Impact of urbanization on CO_2 emissions in emerging economy: Evidence from Pakistan. *Sustain. Cities Soc.* **2019**, *48*, 101553. [CrossRef]
92. Qin, L.; Aziz, G.; Hussan, M.W.; Qadeer, A.; Sarwar, S. Empirical evidence of fintech and green environment: Using the green finance as a mediating variable. *Int. Rev. Econ. Financ.* **2024**, *89*, 33–49. [CrossRef]
93. Udeagha, M.C.; Muchapondwa, E. Green finance, fintech, and environmental sustainability: Fresh policy insights from the BRICS nations. *Int. J. Sustain. Dev. World Ecol.* **2023**, *30*, 633–649. [CrossRef]
94. Yan, H.; Qamruzzaman, M.; Kor, S. Nexus between green investment, fiscal policy, environmental tax, energy price, natural resources, and clean energy—A step towards sustainable development by fostering clean energy inclusion. *Sustainability* **2023**, *15*, 13591. [CrossRef]
95. Dauvergne, P. Globalization and the environment. *Glob. Political Econ.* **2005**, *2*, 448–478.

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Review

Exploring the Interplay Between Energy Policies and Sustainable Development Goals Within Lithuania's Energy Sector: A Critical Review

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Abstract: This paper presents a critical review of Lithuania's climate change mitigation policies within the energy sector, focusing on their alignment with Sustainable Development Goals (SDGs). This study highlights the significance of energy efficiency, renewable energy, and energy security in Lithuania's efforts to reduce greenhouse gas emissions and transition to a sustainable energy system. The review analyzes the selected research literature that studies Lithuania's efforts to adapt and fulfill EU energy directives and national goals, emphasizing the impacts of these policies on various sectors, including residential, transport, and industry. The methodology includes a comprehensive analysis of the existing literature and semi-structured interviews with stakeholders regarding their perceptions of the current state and future directions of Lithuania's energy policies. Findings indicate substantial progress in renewable energy adoption and energy efficiency improvements, contributing to SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). However, challenges such as high costs, underdeveloped financing mechanisms, and limited public awareness hinder further advancements. This paper suggests that future policies should focus on overcoming these barriers, enhancing public engagement, and integrating technological innovations to achieve more significant energy savings and GHG reductions. Recommendations for policy improvements and further research directions are also discussed.

Keywords: energy policies; energy efficiency; renewable energy; energy security; Sustainable Development Goals (SDGs)

1. Introduction

The effects of climate change on the global stage demand urgent and collaborative actions across all sectors of human activity. The world is seeing more frequent and severe consequences of rising greenhouse gas (GHG) emissions, such as record-breaking heat waves over both land and ocean, severe floods, major hurricanes, and extreme wildfires [1]. Among all economic sectors, the energy sector stands as a major contributor to climate change, but it also stands as a pivotal player in the mitigation and adaptation strategies set to reach the ambitious climate targets of the Paris Agreement [2]. Overall, the energy sector has a fundamental role in economic and social development, and the global reliance on it accelerates global warming as it exacerbates environmental degradation, posing a direct threat not only to ecosystems but also to human well-being.

Daily human activities heavily depend on the use of fossil fuels, which has resulted in an excessive rise in carbon dioxide levels and other energy-related GHG emissions. Despite previous efforts and targets set during global climate panels, the prediction for energy demand trends indicates an increase, attributed to economic growth and the rising population. Starting at 30 gigatons (Gt) of carbon dioxide (CO_2) emissions annually in 2010, forecasts suggest that without measures to limit emissions, the carbon dioxide emissions linked to fossil fuel utilization from the energy supply sector as well as energy consumption

in transportation, industry, and buildings could reach 55–70 $GtCO_2$ per year by 2050 [3,4]. Only in Europe, considering the countries that constitute the European Union (EU-27), the total emissions of GHGs in 2021 were 3.5 billion metric tons of carbon dioxide equivalent ($MTCO_2e$), to which the energy supply sector was the lead contributor, having emitted a total of 902 $MTCO_2e$ [5]. With the aim of combating the rising GHG emissions by at least 55% by 2030 in comparison to 1990 levels, the EU adopted a set of commission proposals to their climate, transport, taxation, and energy policies. This implementation, better known as the European Climate Law, can lead to a spur of sustainable economic growth and an accelerated clean energy transition, as well to the improved well-being of EU citizens [6].

Lithuania became a Member State of the EU in 2004, and it is committed to reaching the 2030 European Union climate and energy targets. To ensure the implementation of EU and international agreements to achieve climate change mitigation and adaptation goals and objectives, in 2021, Lithuania approved the National Climate Change Management Agenda (NCCMA). The agenda contemplates targets for GHG emission reductions in the short term (30% until 2030 compared to 2005), mid-term (85% until 2040 compared to 1990), and long term (net-zero until 2050) [7,8]. These goals are ambitious to achieve for the Baltic State as its energy mix remains highly dependent on fossil fuels and electricity imports (about 70% of gross electricity consumption [9]); they are also ambitious due to the increased consumption of energy that the country has seen since 2015, which corresponds to a 2% increment yearly [10]. By 2022, Lithuania's total energy consumption per capita was 2.4 tons of oil equivalent (toe) and the overall energy consumption was 6.8 Mtoe, which accounted for approximately 19.3 $MtCO_2e$ of GHG emissions [11,12]. Recognizing the obligation to tackle climate change and reduce GHG emissions, the country is committed to improving their energy infrastructure and practices addressed in national energy laws and regulations, emphasizing the importance of sustainable practices, innovation, and international collaboration [13].

Addressing climate change in the energy sector is fundamental for shaping a sustainable and resilient future [14]. Transitioning to cleaner, renewable energy sources is not merely an environmental necessity but a strategic act for curbing the increasing threats posed by climate change. The Sustainable Development Goals (SDGs), adopted by United Nations Member States in 2015, are a set of 17 goals "aiming to end poverty, protect the environment, and ensure prosperity and peace for all by 2030" [15]. "Affordable and clean energy", the 7th Sustainable Development Goal (SDG7) adopted by the United Nations in 2015, "aims at ensuring access to affordable, reliable, sustainable, and modern energy for all" [16], and is intricately linked to poverty reduction, health improvements, and economic development. Additionally, SDG 13, "Climate Action", highlights the urgency of addressing climate change, emphasizing the importance of integrating sustainable practices in all sectors [17]. Considering that Lithuania's main energy policy goal is "to ensure energy security at competitive prices with the lowest possible environmental impact" [8], SDG 7 and 13 align with the country's energy strategies, such as achieving energy independence that can be fulfilled by the transition to renewable energy sources, for example, wind and solar power. Furthermore, Lithuania's energy transition is supported by policies that support investment in green technologies [18] and energy efficiency that aligns with broader environmental objectives under the SDGs, including building sustainable cities and communities (SDG 11) [19], and "building resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation" (SDG 9) [20].

Based on this inherent interconnection, this study aims to examine how Lithuania's energy policies facilitate the achievement of the SDGs by conducting a critical review of available literature that focuses on any of the three policy areas of interest to this study: energy efficiency, renewable energy, and energy security. The selected literature covers development of the specific fields including, but not limited to, frameworks, reviews, case studies at local level, and comparative assessments, from 2010 to 2024. The article discusses relevant aspects such as policy implementation challenges, the role of technological innovations, policy adaptability and flexibility, and public perceptions. To have a

deeper understanding of the perceptions of the country's energy policies, the researchers conducted a qualitative survey directed at stakeholders from the private energy sector, private industry, and local governments. Insights from the participants contributed to having closer and more sensible feedback about policy implementation challenges in the country, complementing the focus of this research.

The paper is structured in the following way: in Section 2, an overview of Lithuania's climate change, energy sector, and energy policy status is presented, followed by the methodology implemented to perform this study in Section 3. Section 4 presents the results of the critical review, and the analysis of these studies with relevant SDGs. Section 5 presents the Discussion Section, including the main takeaways from the survey conducted and recommendations for future research.

2. Climate Change, Energy Sector, and Energy Policy in Lithuania: Some Background

2.1. Climate Change and the Energy Sector in Lithuania

Lithuania is situated along the eastern shore of the Baltic Sea. The country's climate is influenced by the Atlantic Ocean and westerly airflow due to its geographical location and flat topography. The country experiences an average annual temperature of 6.9 °C, and relatively high precipitation levels, with higher levels presented in the western part of the territory. The Baltic Sea coast region of Lithuania is especially vulnerable to climate change, with concerns including rising sea levels, storms, hurricane winds, warming of the sea and Curonian Lagoon waters, and changes in salinity [21–23].

Over the past decades, Lithuania has experienced noticeable changes in its climate, indicated by rising temperatures and alterations in precipitation trends. Winters have become milder, with a decrease in the duration of snow cover, while summers have witnessed more frequent heat waves [24]. Figure 1 shows a historical trend of mean annual temperatures recorded in Lithuania's capital city, Vilnius, from the year 1778 to 2021.

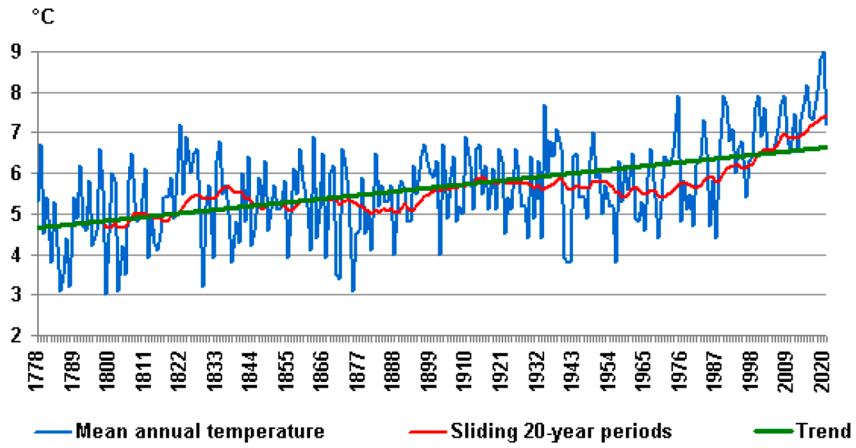


Figure 1. Average annual temperature in Vilnius, 1778–2021. Source [25].

The long-term trend represented with the green light depicts a clear increase in mean annual temperatures, indicative of warming over time. The red line, representing the sliding 20-year periods, highlights periods where the mean temperature deviated from the average. From the blue trend line representing the mean annual temperature for each year, it is notable that in the last 30 years the sharp rise in the mean temperature in Lithuania aligns with the global patterns of climate change. According to Lithuania's Ministry of Environment prediction models, the highest changes in average minimal and maximum temperatures should occur during the cold season, with values as high as 4 °C above the current levels by the year 2100. With these changes, it is expected that the country will experience more heatwaves (days when the temperature rises above 30 °C) during the hot season while cold spells will become less frequent (days when minimal temperature

falls beneath −15 °C). These shifts in climate patterns have direct implications for various sectors, including agriculture, water resources, and energy [23,25].

Lithuania's energy sector has historically been a significant contributor to the country's climate change due to its reliance on fossil fuels for electricity generation and heating [26]. The country has been heavily dependent on imported oil, natural gas, and coal, leading to substantial greenhouse gas emissions [9]. In 2020, the energy sector contributed as a source of GHG emissions in Lithuania with a share of 58.5% of the total emissions, excluding Land Use, Land Use Change, and Forestry (LULUCF), as represented in the left pie chart of Figure 2. Focusing on the Energy sector depicted in the right pie chart of Figure 2, the largest share of emissions comes from the "Transport" sector, followed by the "Energy Industries" sector, at 13.1%. Combined, the "Manufacturing Industries and Construction", "Fugitive emissions from Fuels", and "Other sectors" contribute 14.8% to the emissions pie. Emissions from the energy sector include CO_2, CH_4, and N_2O GHG. The most significant GHG during the same year was CO_2, which contributed 67.6% of the total national emissions of CO_2eq. In 2020, CO_2 emissions stemming from the energy sector represented 82.1% of the nation's total CO_2 emissions. Within this, transportation and energy industries were the primary contributors, accounting for 45.0% and 19.4% of the nation's total CO_2 emissions, respectively [25]. Lithuania's GHG emissions increased by 8.8% per inhabitant between 2005 and 2019, while during the same period, EU levels decreased by 22% [27]. Several factors contributed to the rise in emissions levels in the country during that period, including the Ignalina Nuclear Power Plant shutting down in 2010, which incurred larger oil product imports, with a share of 36.2%, surpassing the percentage of the previous decade which fluctuated around 32.6% [25,28].

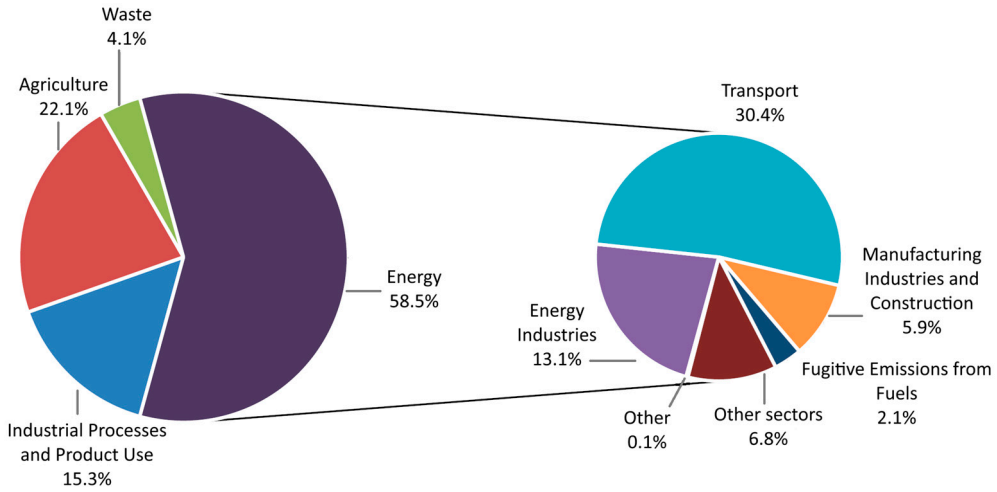


Figure 2. Lithuanian GHG emissions (CO_2eq.) by sector (excl. LULUCF) in 2020. Source [25].

One of the key factors driving Lithuania's emissions in the energy sector is its aging infrastructure and inefficient energy systems. Outdated power plants and heating facilities, coupled with inefficient energy usage in residential, commercial, and industrial sectors, have led to higher emissions per unit of energy produced or consumed. Additionally, the dominance of conventional energy sources has limited the incorporation of renewable energy alternatives, further exacerbating the carbon footprint of the energy sector [13,29]. Despite the active challenges, Lithuania has been focusing on diversifying its energy sources, increasing energy efficiency, and integrating renewable energy into its grid, aiming for sustainability and energy independence. This approach not only contributes to reducing greenhouse gas emissions but also strengthens Lithuania's energy security, reducing its reliance on imported fossil fuels [13].

2.2. Climate and Energy Policy in Lithuania

Lithuania's climate policy aligns with the EU's Climate and Energy Framework (2014) that set the goal of reducing EU-wide GHG emissions by 40% by 2030 in comparison with 1990 levels. The framework required all member states to present National Energy and Climate Plans (NECPs) that set a ten-year plan detailing each member's contribution to the EU's 2030 climate targets. Lithuania adopted the NECP from 2021 to 2030, which details a series of steps aimed at achieving various policy goals such as decarbonization of the energy sector, enhancing energy efficiency and increasing the use of renewable energy in public and residential buildings, reducing the population's energy poverty, and becoming a leader in energy technology innovation to ensure energy security. The NECP was developed in parallel with the 2021–2030 National Progress Plan, the objective of which is to assess the country's long term development goals and priorities to ensure progress in social, economic, environmental, and security areas. For long-term action in the period of 2030–2050, Lithuania adopted the National Energy Independence Strategy (NEIS) in 2012. The NEIS's main strategic goals are "to increase the share of electricity production from RES (renewable energy systems) in the final electricity consumption up to 45% in 2030 and 80% in 2050" [8,29,30]. Table 1 summarizes the energy and climate targets of Lithuania that are contained in the NEIS and the NECP. For the mid-term period, Lithuania's goals are to reduce non-ETS (Emissions Trading System) sector emissions by 9% compared to 2005. For the long-term period, the country must increase the total share of renewable energy systems (RESs) in the total gross energy consumption by up to 80%. For medium- and long-term objectives, Lithuania aims to cut GHG emissions by at least 40% by 2030 and to become carbon neutral by 2050 from 1990 levels, with 20% of reductions coming from land use and forestry sectors [7,13,29].

Lithuania's general energy policy objective is to guarantee sustainable energy security provided at competitive prices [31] that aligns with the international climate agreements and the SDGs. As the purpose of the study is to analyze the interplay between energy policies and sustainable development, Table 1 presents the targets contained within the NEIS and the NECP for the years 2030 and 2050, along with the SDGs relevant to the National Progress Plan main energy-focused objectives [13]:

1. To enhance environmental quality and resource sustainability, reduce Lithuania's contribution to climate change, and raise its climate resilience;
2. To improve the energy sector's competitiveness;
3. To merge Lithuania's natural gas market with the single EU gas market;
4. To connect Lithuania's power grid with the continental European grid to enable synchronized operation;
5. To maintain and improve the reliability and local contribution of the Lithuanian electricity market and power system;
6. To reduce energy poverty among the population;
7. To expand the use of renewable and alternative fuels in the transportation sector and support sustainable intermodal mobility;
8. To raise the proportion of renewable energy used in national energy production and gross energy consumption and implement measures to cut down pollution in the energy sector;
9. To enhance energy efficiency and the utilization of renewable energy in residential and public buildings.

Table 1. Interplay between NEIS/NECP targets and SDGs. Adapted from [29], Table 2.1; adapted from [13], Table 1.1.1.

NEIS/NECP Targets	2030	2050	NPP ** Objectives	SDGs
GHG reduction under the Doha amendment to the Kyoto protocol and Paris Agreement, compared to 1990 level	At least −40%	Net zero	1, 6, 8	7.1, 9.1, 11.b ***, 13.2

Table 1. *Cont.*

NEIS/NECP Targets	2030	2050	NPP ** Objectives	SDGs
GHG reduction in the EU ETS sectors compared to 2005 level	−43%	--	1, 8	13.2
GHG reduction in the EU non-ETS sectors compared to 2005 level	−9%	−95% (energy and transport)	1, 6, 8	13.2
Share of RESs in gross final energy consumption	45%	80%	8, 9	7.2, 8.2
Use RESs in transport	15%	50%	5, 6, 7	7.2, 11.2
Electricity interconnection	15%	--	4	7.a ***, 7.b
National contribution for energy efficiency (in Mtoe) - Primary energy consumption - Final energy consumption	PEC—5.4 FEC—4.5	Reduce primary and final energy intensity * by 2.4 times (from 2017 levels)	6, 8, 9	1.2, 7.3

* Energy intensity is often used to measure energy efficiency, and it is calculated as units of energy per unit of GDP [32]. ** National Progress Plan. *** targets a and/or b of the SDG.

3. Methodology

This section outlines the systematic approach used to conduct the critical review, which explores the interplay between energy policies and Sustainable Development Goals (SDGs) within Lithuania's energy sector. The critical review aims to analyze the existing body of knowledge related to Lithuania's energy policies and their alignment with SDG7 (Affordable and Clean Energy) and other relevant SDGs. The review method follows a qualitative approach, where data from various sources are compared and critically assessed.

The review process involved collecting data from academic journals, reports, case studies, and policy documents. The first step of the process was to collect the data from the chosen databases, "Elsevier's Science Direct" and "Google Scholar", using the following keywords defined for the search: "energy efficiency", "renewable energy", "energy security", "Lithuania", and "energy policies". Boolean operators (AND, OR) were used to combine different terms, and filters were applied to limit results to publications between 2010 and 2024 and English language articles. The period from 2010 to 2024 was selected with the purpose of covering an important energy transition period in the country marked by the shutting of the Ignalina Nuclear Plant in 2009. Many results came back from the strings: Science Direct (n = 113) and Google Scholar (n = 13,140). All results from Science Direct were scoped to determine if a further analysis was pertinent. Only the first 150 search results from Google Scholar were scoped to determine if further analysis was pertinent.

The literature was selected based on three main inclusion criteria: (1) publications related to the energy sector in Lithuania, and covering policy implementation and/or impacts in the context of any of the three main focus areas, that is, EE, RE, and ES; (2) studies which indicate a relationship between energy policies and one or more SDGs, especially SDG 7 and SDG 9; (3) articles that provide quantitative or qualitative data regarding EE, RE, or ES outcomes or case studies relevant to the Lithuanian context. The exclusion criteria were the following: (1) literature not directly related to Lithuania's energy sector and to at least one of the focus areas defined; (2) publications in languages other than English. Once the initial pool of literature was selected, the next step was to conduct a screening of their titles and abstracts. Articles and documents that did not cover the inclusion criteria were no longer considered. The following step was to read the articles in full to assess their depth of analysis, methodological rigor, and relevance to the Lithuanian energy sector. After completing the reading, the documents were classified in the three focus areas to facilitate the critical analysis by comparing their results regarding the success of policy implementation, as well as shortcomings and potential alignment with SDGs. The critical review and the analysis of synergies between energy policies and SDGs are presented separately in Section 4. The implemented methodology is presented in Figure 3.

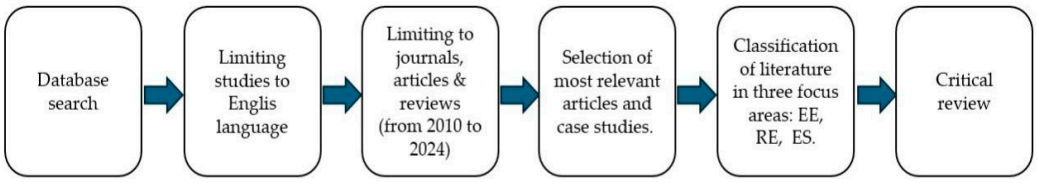


Figure 3. Methodology.

To broaden the scope of the review, four semi-structured interviews were conducted on stakeholder perceptions of energy policies in Lithuania. These surveys included both the positive aspects of policy implementation and the perceived drawbacks, as well as possible ways for improvement. The interviews with the participants were conducted via email and via video call, with those who agreed to meet with the interviewer. The questions addressed in the survey are available in Appendix A of this document, while Table 2 summarizes the arrangement of the survey, maintaining the anonymity of the participants based on their request. The answers to the questions were obtain in both the English language and Lithuanian language, and the results of the interviews are analyzed in the Discussion Section of this article.

Table 2. General description of interview design. Adapted from [33].

Participant Function/Entity	Method of Contact	Date of Survey
Sustainability partner, energy industry	Video call interview	27 September 2024
Legal counsel, private production company	E-mail interview	7 October 2024
Member of National Network of Green Municipalities	E-mail interview	27 September 2024
Director of smart energy consulting company	E-mail interview	3 October 2024

4. Critical Review and SDGs Analysis

4.1. Critical Review of the Literature

4.1.1. Energy Efficiency

Until the year 2010, the Lithuanian energy sector was characterized by energy generation capacities that exceeded the national demand. The turning point at the end of 2009, caused by the closing of Ignalina Nuclear Power Plant, directed the country to become dependent on energy imports of both electricity and natural gas [34]. Because of the plant closure, the main energy policy of Lithuania, the Law on Energy Efficiency, was reviewed, carrying with it the strengthening of energy structure development, like a high-voltage grid interconnection with other member states that launched later in 2017 [35]. Shortly after, in 2012, the Energy Efficiency Directive 2012/27/EU was proposed with the main goal of achieving a reduction of 20% in primary energy consumption by 2020 [36]. Currently, the NEIS is the country's leading energy policy document that, in the area of energy efficiency, aims to achieve a primary and final energy intensity that is 1.5 times lower than the 2017 level by 2030, and approximately 2.4 times lower by 2050, as specified in Table 1.

In the study conducted in [37], the authors focused on the evaluation of energy efficiency policies in Lithuania within the context of EU directives and national goals. The document emphasizes the need for a clear distinction between energy intensity reduction due to efficiency improvements and the downscaling of energy-intensive activities. The research highlights specific programs and measures, such as the modernization of apartment complexes, renovation of public buildings, voluntary agreements with industry, and infrastructure improvements in the transport sector. To evaluate the success of energy efficiency policies, the authors established three main categories: effectiveness (achieved energy savings, in GWh), efficacy (achieved savings compared with targets, %), and cost efficiency (achieved energy savings compared with costs, KWh/LTL). The most significant energy savings found were reported in the service sector, while the energy production

sector ranked second. However, they noticed that the potential for energy savings in the household sector, particularly through behavioral changes, was underutilized. They also found that the economic efficiency of implemented energy efficiency policies was low, indicating the need for more cost-effective policies and measures, especially in the transport sector. Their comparative assessment indicates that while some sectors have successfully met or exceeded their energy-saving targets, others, like the household and energy sectors, have fallen short, pointing to the need for revised or additional measures to meet national and EU energy efficiency goals. Additionally, for this sector, the authors identified significant energy-saving potential through behavioral changes, such as information campaigns and home energy audits. These measures are practical and can be implemented at relatively low costs.

The research conducted in [37] set a broad and inclusive approach to the Lithuanian energy policies. By the time of the study, the author was able to identify a lack of harmonization between policies addressing energy efficiency and climate change mitigation. Similar studies carried out in [38,39] also point out that the primary focus of energy efficiency and climate change mitigation policies in the EU and Lithuania had been on the supply side of energy and industrial users, highlighting that household efficiency has a significant potential of study for policies implementation. The focus on residential infrastructure is especially important in Lithuania because buildings make up a large share of the country's energy consumption. By 2021, there were 1.4 million dwellings in Lithuania, of which only 167,000 were built after 1995, which translates into old infrastructure with poor insulation materials, outdated heating equipment, and poor or non-existent bioclimatic design [29,40].

In [38], researchers turned their study to the critical role of households in energy savings and sustainable use. They continued the analysis presented in [37], showing how behavioral changes and the adoption of energy-efficient appliances are two ways in which households can contribute to energy-saving and reduction in GHG emissions. The research uses an interesting approach to evaluate energy policies: SWOT (Strengths, Weaknesses, Opportunities, Threats) and PEST (Political, Economic, Social, Technological) analyses. This approach is beneficial, because it serves to assess the effectiveness of Lithuania's climate change mitigation policies across various sectors, including housing, transport, energy, and education. Through the SWOT analysis, the paper identifies the strengths of Lithuania's policies in promoting energy efficiency in apartment buildings and transport, as well as in raising public awareness through various media and educational programs. The use of correlation analysis to identify the impact of various drivers on energy consumption across different countries (Lithuania, The Netherlands, the United Kingdom, Germany) is a robust methodological choice, offering comparative insights. The research detected weaknesses in policies, for instance, the excessive costs of technology, underdeveloped financing mechanisms, and a general lack of knowledge within the population, which slow down the implementation of energy-saving measures. The PEST analysis complements this by looking at the macro-policy environment and strategic planning tools that can select new policies. It emphasizes the influence of political stability, tax rates, social values, technological advancements, and innovation on energy consumption and savings behavior. The researchers concluded by suggesting that Lithuania's GHG emission reduction efforts should primarily be directed towards improving energy efficiency, parallelly highlighting that this goal can only be achieved when the gap between the legislative framework and implementation of concrete measures is closed.

Another interesting case study that assesses potential energy savings in the Lithuanian building sector is presented in [39]. The study provides a comprehensive analysis aimed at evaluating feasible energy savings in space heating and hot water by 2030, emphasizing energy efficiency solutions for a total of 30 building types. The research employs various cost curves to represent both investor and overall economic perspectives on energy savings potential. The methodology includes analyzing the Lithuanian building inventory, calculating energy demand, evaluating the cost-effectiveness of investments, and deriving cost curves based on a comprehensive data set that includes the decomposition of supplied

energy for buildings: biomass, coal, district heat, gas, and oil. The study concludes that a 56% reduction in final energy demand is achievable by 2030 if least-cost energy efficiency solutions are selected for each building type. Specifically, implementing energy performance class A measures in pre-1990 apartment buildings supplied by district heating emerges as the most cost-effective technological strategy. In line with the findings of [37–39], the study underscores the need for policies that encourage building renovation, particularly focusing on structures with low energy performance, and promote deep renovation to prevent lock-in effects and facilitate the transition to nearly zero-energy buildings. The robust methodology presented in [39], which combines the Fisher Ideal Index and Logarithmic Mean Divisia Index, provides a solid foundation for analyzing energy intensity and GHG emissions.

Up to now, we have analyzed how national energy plans, energy efficiency programs, and related planning documents typically include goals and strategies aimed at reducing energy intensity [35]. Energy intensity is known as the most common indicator to measure changes in energy efficiency [32]. The possibility of energy intensity reduction differs among countries and is conditioned by factors inherent to their characteristics, but it is possible to compare trends and drivers, especially if similar or the same policies are adopted. The study performed by Ref. [41] explores the strategic importance of enhancing energy efficiency in the Baltic countries—Estonia, Latvia, and Lithuania—as a vital component of transitioning to a low-carbon economy. The paper inspects the trends in energy intensity from the years 2000 to 2018 within the context of the EU's energy and climate framework and analyzes variations in the energy intensity of these countries in three principal areas: primary and final energy intensity, and sectoral energy intensity. The study employs the Fisher Ideal Index to discern contributions from increased energy efficiency and structural changes within these economies. Three main strengths can be listed for the research conducted in [41]: (1) the analysis spans nearly two decades, providing a broad view of energy efficiency trends and their implications for sustainable energy sector development; (2) utilizing the Fisher Ideal Index adds a layer of depth to the analysis, allowing for a better understanding of how energy efficiency improvements and economic structural changes have contributed to trends in energy intensity; (3) the paper goes beyond aggregate measures, investigating sector-specific energy intensity trends, which is crucial for targeted policy interventions. Although the progress made by the Baltic States in reducing energy intensity is significant, the sector-specific analysis suggests that targeted interventions in sectors like transportation and industry could produce substantial energy savings.

The research of Ref. [42] examined energy intensity and GHG emissions in the three countries—Lithuania, Latvia and Estonia—focusing specifically on the manufacturing sector during the period of 2010 to 2020. The researchers carried out a study of how improvements in energy efficiency and shifts in the structure of manufacturing activities within those countries impacted their energy consumption rate, achieved overall energy savings, and reduced GHG emissions. The research methodology starts by analyzing time series data for energy consumption within the manufacturing industry of each country and calculating their energy intensity. By doing so, the authors identified how the influences of various factors such as labor productivity and improvements in the consumption of fossil fuels contribute significantly to the sector's progress in mitigating climate change. The decomposition analysis of GHG emissions indicated that lower energy intensity and reduced fossil fuel use played a key role in cutting GHG emissions across the three Baltic countries. However, these efforts seemed to be somewhat offset by the rise in the production rate during the examined timeframe which led to an increase in personnel and emissions intensity. The authors conclude by stressing the importance of incorporating RESs in all sub-sectors of the manufacturing industry to further enhance the decrease in GHG emissions. This study offers valuable insights into the specific contributions of different drivers to changes in energy intensity and GHG emissions, which can inform targeted policy interventions. However, while the paper points out the necessity for updated policies, it could benefit from a more detailed exploration of specific policy recommendations and

strategies to address the identified challenges. Further studies could explore the impact of emerging technologies and innovations in the manufacturing sector to achieve national and EU emissions targets.

4.1.2. Renewable Energy

The correlation between energy efficiency and renewable energies is a keystone of the global transition towards sustainable energy systems. While both are critical for reducing GHG emissions and mitigating climate change, they function in complementary ways that together enhance the overall sustainability of energy systems [43]. By 2030, Lithuania aims to have a minimum of 45% of its energy consumption sourced from renewable energy. By 2050, the government is aiming to achieve 80% of the overall energy demand from renewable sources and to reach 100% renewable energy usage in electricity generation, as shown in Table 1.

The study of Ref. [44] is a thorough analysis examining the GHG emission trends and the efficacy of climate change mitigation policies in Lithuania and Bulgaria's fuel combustion sectors. The study emphasizes that, despite having comparable economic statuses and historical backgrounds, the two countries have adopted key EU energy and climate policies, yet have experienced different degrees of success in reducing GHG emissions. The document begins by asserting the cruciality of climate policies in the EU's energy sector, noting that fossil fuel combustion remains the leading human-caused contributor to GHG emissions. Later, it presents a comparative analysis by examining reports to the United Nations Framework Convention on Climate Change, delineating the key areas and potential for GHG emission reduction, as well as the driving forces behind these changes. An observation from the study is the difference in the effectiveness of the mitigation policies between the two countries. Bulgaria's policies, which prioritize switching from coal to natural gas, are less efficient than Lithuania's, which focus on improving energy efficiency and integrating renewable energy sources. The analysis delivered by Ref. [44] helps in understanding the complexity of implementing climate change mitigation policies in transitioning economies, and it serves as a reference to demonstrate the efficacy RESs can achieve over conventional energy sources.

The research of Ref. [45], different from Ref. [44], adopted an economic perspective. Their primary aim was to assess whether and how the use of RES impacts Lithuania's real GDP, with a particular focus on calculating the elasticity coefficients of real GDP to RES use. The study employs unit root tests, co-integration tests, and Granger causality tests to analyze the relationship between the two variables. These methods help determine the stationarity of the time series, the long-term equilibrium between the variables, and the directionality of any causal relationships. The analysis reveals a unidirectional causality running from RES use to real GDP in the short term, suggesting that increased employment of RESs could positively impact Lithuania's economic growth in the short term. However, a long-term effect of RES development on real GDP was not found. Because the study of Ref. [45] centers on a specific country and period, it allows a detailed insight into Lithuania's national context. This narrow analysis facilitates national policymakers to use the study as a reference to explore the interrelationship between RES and economic growth.

Ref. [46] presented results through the implementation of the NEIS targets and EU Directive 2009/28/EC on the encouragement of RES adoption. The authors examined the changes in Lithuania's total inland fuel and energy consumption from 2012 to 2017, revealing an increase in the proportion of renewable and domestic energy sources from 19.4% to 24.6%, and a rise in electricity's contribution from 7.7% to 9.7%. Their research shows that during this period, the share of renewable energy sources in total final fuel and energy consumption grew from 21.4% to 25.6%. Additionally, the percentage of RESs in gross final electricity consumption rose from 10.9% to 16.8%, and in total heating and cooling usage, it increased from 34.6% to 46.5%. Although the largest quota of RESs in the country came from biofuels, like wood and agricultural waste, wind energy performed second as a source of alternative fuels with a change from 2000 to about 5000 TJ of produced energy

for the period of the study. At the same time, the authors analyzed the change on GPD in Lithuania, which increased 1.3 times from 2012 to 2017, as a measure to assess economic development and as a way towards energy security and independence. These results can help corroborate the research of Refs. [44,45] by demonstrating how implementing assertive RES policies in transitioning economies can boost GHG emission reduction while having a positive impact in economic growth.

While it is important to focus on the evolution of RES implementation in a specific country, it is worth comparing results obtained in geopolitically similar nations and assessing the differences in EU policies across its Member States. The studies conducted on [47,48] focus on the results that energy policies have in the Baltic States—Lithuania, Latvia, and Estonia—from an RES perspective. On one hand, Ref. [47] provides a systematic examination of RES deployment trends in the three member states from 2010 to 2019, effectively contextualizing these trends within EU energy policies, particularly the Renewables Directive 2009/28/EC. By 2019, the share of RESs in the gross final energy consumption within the Baltic States surpassed the minimum targets set in the directive. All countries' results were positive with different percentages of the achieved share of RESs. Lithuania surpassed the mandatory target by 10.7%. The study also demonstrates that the proportion of RESs in the final energy consumption for cooling and heating in Lithuania was higher than planned in Lithuania by 20.1%.

On the other hand, Ref. [48] offers a comprehensive analysis of the achievements of the Baltic States in meeting the EU's 20-20-20 climate and energy targets, which included a 20% cut in GHG emissions from 1990 levels, ensuring 20% of energy consumption from RESs, and achieving a 20% improvement in energy efficiency by 2020. The research of Ref. [48] developed an indicator framework consisting of three areas: energy efficiency, renewable energy, and GHG emissions reduction. The indicators' description and relevance were summarized in a table to facilitate differentiation and tracking. The results in [47,48] highlight that while the Baltic States have met the 20-20-20 targets, the levels of achievement vary among the countries, with Lithuania showing the second overall performance, after Latvia. Nevertheless, all three member states compared poorly in comparison with general EU levels, with the energy intensity as high as double the EU-27 average. The variation in energy intensity is attributed to differing national policies, economic structures, and resource availability. Both Refs. [47,48] stress the achievement of the Baltic States in increasing their share of renewables in their energy mix, attributing part of the success to the transition from Soviet-era outdated and inefficient systems.

An applied study conducted by Ref. [49] assessed the contribution of local-level initiatives in Lithuania towards sustainable energy development and climate change mitigation. It specifically examines the role of renewable energy in this context by analyzing Sustainable Energy Action Plans (SEAPs) from various Lithuanian municipalities. The research employs a mixed-method approach, combining SWOT analysis with expert surveys to evaluate the effectiveness of SEAPs. This approach enables a comprehensive understanding of the strategic position and the practical implications of local renewable energy initiatives. The SWOT analysis conducted on the SEAPs indicates a range of strengths, including existing legal frameworks and infrastructures that support renewable energy development. However, weaknesses such as insufficient funding, lack of coherent policies at the municipal level, and inadequate public awareness about renewable energy benefits are notable obstacles. The expert survey emphasizes the prioritization of building renovations and the modernization of energy infrastructure to enhance energy efficiency. One of the main takeaways from this paper is the identification of contradictions between state and municipal legal acts and energy security objectives. Another important finding is the impossibility of fully developing renewable energy projects at the rural level for economic and legislative issues, which are controlled by the government or municipal councils. Even when Lithuania has adopted legal acts that aim at implementing renewable energy technologies, the researchers maintain that there is no allocation of funds to secluded or small cities, forcing the citizens to continue using fossil fuels for their daily activities.

4.1.3. Energy Security

Russia's illegal invasion of Ukraine ratifies the necessity for energy security for all Member States of the EU [50]. This pressing event locates energy security at the same level of importance as energy efficiency and renewable energies. Considering the long and distressing history between the Baltic States and Russia, it is pertinent to underscore the urgent need to reinforce measures and policies that help speed up Lithuania's energy transition and terminate energy imports from the Russian Federation.

In the research conducted by Ref. [51], scholars explored Lithuania's transition from high dependency on imported electricity to renewable energy sources as part of its national energy strategy. The study scrutinizes the Copenhagen Securitization Theory to examine how perceptions of energy security have influenced Lithuania's shift in energy policy. According to the Copenhagen theory, energy politics and policies are directly determined by the socially constructed perception of energy security. The research states that about 70% of Lithuania's electricity consumption had been generated abroad by a single provider, Russia, until 2015. Despite Lithuania's initial pro-nuclear stance, the country transitioned to a renewable-focused national energy strategy within a decade. The research suggests that this shift was driven by concerns over potential energy security risks. The document traces the political processes that led to two distinct national energy strategies between 2009–2012 and 2013–2018. The findings indicate that the adoption of renewable energy policies was not directly due to energy security concerns related to dependency but rather followed the de-securitization of energy supply. The researchers present an insightful geopolitical analysis, suggesting that the war-related crisis in Eastern Europe could affect the landscape of renewable energy adoption, potentially deterring the transition due to amplified energy security concerns.

It is worth highlighting how Ref. [51] challenges the notion that direct energy security concerns drive renewable energy adoption. Instead, it suggests that a level of perceived energy security must first be established before renewables become a central part of energy strategy. Going deeper into the Lithuanian case, it is a good suggestion from the study that the transition towards renewable energy in the country appears to be influenced by a combination of internal policy shifts and by external geopolitical factors. This perception provides valuable insights for other countries and regions facing similar energy security challenges, suggesting that the path to renewable energy adoption might first require addressing and mitigating immediate security concerns.

Before the geopolitical conflicts that escalated in 2022 between Ukraine and Russia, and consequently the EU, studies conducted in the Baltic States were already assessing the influence that energy efficiency, renewable energies, and energy import dependence had in achieving energy security. The research by Ref. [52] provides an analysis of energy security trends across Estonia, Latvia, and Lithuania during the period from 2008 to 2012. The study employs multi-criteria decision-making techniques to develop aggregate measures of energy security, using a range of indicators—economic, social, and environmental—aligned with the priorities of European Union energy policy. This approach, which incorporates both Data Envelopment Analysis-linked and modified Simple Additive Weighting methods for weight calculation, is tough and innovative because they increase the objectivity and reliability of the analysis. The simultaneous comparison between the three countries' energy security status shows that Lithuania performed very poorly in terms of energy dependency indicators, despite having a decent performance of renewable energy and carbon intensity indicators, in comparison with Latvia and Estonia. Considering that previous similar studies on energy security in the Baltics had only focused on energy storage and security of supply [53,54], this research broadened the perspective on how social, environmental, and economic indicators can be implemented. The comparison among the Baltic States positioned Latvia as the best-performing country in terms of energy security, while previously Estonia had taken the higher rank. This is an insightful takeaway from the study because it provides evidence that limiting or modifying the selection of indicators provides different perspectives, so this result could encourage other researchers

to create different frameworks for assessing policy implementation in terms of the specific case of each country or study group.

For the Baltic Sea region (BSR), and particularly for countries that are heavily reliant on imported energy, ensuring energy security involves diversifying supply sources, reducing dependency on single suppliers, and increasing the resilience of energy infrastructure [55]. The paper by Ref. [56] addresses these concerns through the development and expansion of Liquified Natural Gas (LNG) infrastructure through the lens of the Network of Adjacent Action Situations framework, presenting LNG as a strategic solution to enhance energy security in the BSR. The document emphasizes the polycentric nature of energy governance and highlights how interconnected policy areas influence infrastructural decisions and outcomes. The author highlights the transition from state-controlled to privatized energy infrastructure and the resulting complexities in governance with the use of the Network of Adjacent Action Situations framework, which links multiple policy areas and demonstrates how decisions in one area impact others. According to the author, the LNG infrastructure in the BSR offers a critical alternative to the Russian pipeline gas, enabling countries to diversify their energy sources and enhance energy security by mitigating supply disruptions and geopolitical risks. The development of LNG terminals in Lithuania, Poland, Finland, and Sweden, symbolized by Lithuania's "Independence" terminal, illustrates a strategic push towards greater energy independence and increased bargaining power in the energy market.

Europe's energy dependence on Russia is not limited to Eastern Europe, but also extends to Central Europe and some Western European countries, such as Germany. In the analysis of Ref. [57], the authors examine the impact of Russia's cut of gas supply to EU after the aggression against Ukraine, which accounted for 45% of the block natural gas imports. Germany's response to the supply cut was shifting to piped gas from Norway and LNG via Belgium and the Netherlands. While some countries from the Visegrád Group—like Poland—saw the decrease and eventual ceasing of Russian supply as an opportunity for energy independence, Hungary continued to maintain business with the aggressor country and even increased its imports. With the expansion of LNG capacity, the authors explain how Member States like Germany, Lithuania, Croatia, and Poland could increase their needs from 200 TWh/year to 500 TWh/year. The shift towards RESs came along stronger after the war started, with some easing of regulations to support the initiative so that ambitious plans like Germany's goal to triple wind and solar capacity by 2030, that is, from 440 GWh/day to 1200 GWh/day, might be achieved. Other EU countries, like France, the Czech Republic, Hungary, Slovakia, and Poland plan to expand their nuclear power capacities, which can help in reducing the consumption of fossil fuels, yet these projections are set for the long-term and some of the plants in central European countries still depend on Russian fuel for their operation, perpetuating concerns about energy security through energy weaponization.

In the research of Ref. [58], the authors conducted a broader analysis of energy security goals' effectiveness across all the EU-27 countries between 2010 and 20120, from two different angles: a traditional energy-economical approach and a sustainable energy-security perspective that incorporates environmental and social factors on top of traditional ones. The study starts by setting a list of indicators that characterize energy security from energy, economic, social, and environmental factors. The authors used a Multi-Criteria Decision-Making method to weigh the selected indicators with the combination of Criteria Importance Through Intercriteria Correlation and Standard Deviation methods. A second Multi-Criteria Decision-Making method was implemented to determine an index for assessing the EU-27 in terms of energy security: Gray Relational Analysis and the Technique for Order of Preference by Similarity to Ideal Solution methods. The results show that Scandinavian countries have the highest level of energy security along with France, attributed to the use of nuclear energy. The countries with the lowest performance were Cyprus and Malta due to their practically non-existent self-supplied source of energy. From a sustainable energy-security perspective, countries like Sweden, Finland, Belgium, and the Netherlands performed well. From the BSR countries, only Latvia figured in the list. During all years evaluated in this research, Lithuania showed a poor performance from

both perspectives, and even when there have been improvements in the share of RESs, the study positions the Baltic country in the warning level for energy security.

4.2. Linking Studies to SDGs

Tables 3–5 provide an overview of how the analyzed research studies align with specific SDG targets. They highlight the interconnected nature of energy policies, renewable energy adoption, and energy security with global sustainability goals. The studies collectively support the interplay between SDGs and energy policies: the expansion of renewable energy and improvements in energy efficiency (SDG 7) directly contribute to the reduction of carbon emissions, a primary driver of climate change (SDG 13) by transitioning away from fossil fuels to renewable energy sources and paving the way to achieve energy independence. Implementing SDG 7 can lead to significant co-benefits for climate action, such as reduced air pollution, which in turn has positive effects on public health and productivity (SDG 11). Equally, pursuing SDG 13 by focusing on lowering carbon emissions will often involve strategies that are also favorable to achieving SDG 7, such as promoting the adoption of green technologies and enhancing energy efficiency.

Referring to the literature that analyzes the EE and RE spheres, it can be observed that targets 7.2 and 7.3 are properly covered, which can be linked to the significant efforts of Lithuania to increase the share of RESs by the expansion of alternative energy sources infrastructure such as wind power, and to increase to 80% the total share of renewable energy systems in total gross energy consumption. From the selected literature, it can also be noticed that the efforts to address the inefficiency of old building infrastructure in the country are significant and that simple suggestions like changes in population behavior could result in significant changes for this sector. Then, as previously stated, the progresses of policies addressing energy efficiency are directly linked to innovations of RESs and they need to be constantly reviewed and reconsidered in order to have a proper alignment with technological upgrades.

Table 3. The interplay of the analyzed literature with the SDGs targets—EE.

Research	SDG Targets Addressed
[37]	• Comprehensive overview of Lithuania's energy efficiency policies across multiple sectors—energy production, household, service, and transport. Good performance of sectors to support 7.2, 9.1 in the service sector, and need to improve 11.2 for the transport sector. • The analysis of specific programs and measures, like the modernization of buildings and the promotion of cogeneration, supports targets 11.1 and 11.6, and subsequently contributes to target 13.2.
[38]	• The emphasis on public education and behavioral changes in energy consumption analyzed in this research supports targets 12.8 and 13.2 by promoting sustainable practices and reducing emissions, while directing impacting 7.3, 9.1, and 11.1.
[39]	• The paper emphasizes the need to rush the renovation of pre-1990 apartment buildings in the country and to push for nZEBs, supporting targets 7.3 and 11.3. • The decrease in energy use in buildings leads to lower GHG emissions, which is crucial for mitigating climate change (13.2).
[41]	• The analysis of primary and final energy intensity trends, along with the implementation of cost-effective energy efficiency measures, supports the goal of providing sustainable and modern energy (target 7.1). • By examining the factors that drive energy efficiency, the paper highlights the importance of responsible energy use (12.2).
[42]	• The authors discuss the increasing consumption of RESs in manufacturing, aiming to enhance the share of clean energy in the energy mix (7.2) and emphasize the improvement of EE in the sector, which aligns with the goal of doubling the global rate of improvement in EE (7.3). • The study highlights the structural changes in activities and the deployment of RESs as key drivers in reducing energy intensity and GHG emissions in manufacturing (9.4).

Table 4. The interplay of the analyzed literature with the SDGs targets—RE.

Research	SDG Targets Addressed
[44]	• The article emphasizes energy efficiency measures, like the upgrading of power plants and the promotion of combined heat and power systems, supporting the goal of doubling the global rate of improvement in energy efficiency (7.3). • The paper highlights improvements in EE and the development of low-carbon technologies in the energy sector through the modernization of infrastructure, including district heating systems and smart grids (9.4), and by addressing the reduction in GHG emissions with increased use of RESs (12.2); the article indirectly supports the goal of reducing the adverse per capita environmental impact of cities, and of creating more sustainable environments (11.6). • The study enhances understanding of the drivers and impacts of GHG emissions and the effectiveness of different mitigation policies, contributing to adaptation, impact reduction, and early warning (13.3).
[45]	• The study directly addresses economic growth by examining how renewable energy consumption (7.2) influences Lithuania's real GDP (8.1) and improves global resource efficiency in consumption and production (8.4). • The article supports the modernization and sustainable development of infrastructure (9.4) for the use of RES over fossil fuels (12.2). • The article enhances the understanding of the role of renewable energy in economic growth, contributing to improved education, awareness, and capacity on climate change mitigation (13.2, 13.3).
[46]	• The authors discuss the increase in the proportion of RESs in Lithuania's total inland fuel and energy consumption (7.2) by the development of new infrastructure (9.4, 9.B) like wind power plants, which is projected to produce over 50% of electricity by 2050. • By highlighting the growth in renewable energy production, such as wind and biogas, the article supports the target of doubling the global rate of improvement in energy efficiency (7.3), outlining Lithuania's targets for increasing RESs in final energy consumption for 2030, 2040, and 2050 (13.2), and simultaneously supporting rationalizing inefficient fossil-fuel subsidies that encourage wasteful consumption (12.C).
[47,48]	• The articles discuss the increase in the share of RESs (7.2) in final energy consumption in the Baltic Countries across various sectors. By analyzing the progress towards achieving 20% of renewables in final energy consumption, they promote access to more affordable and modern energy services through a more solid and realistic integration of climate change policies and strategies in the region (7.1, 12.2, 13.2).

Table 5. The interplay of the analyzed literature with the SDGs targets—ES.

Research	SDG Targets Addressed
[51]	• The article discusses Lithuania's transition from high energy dependency on Russia to increased use of RESs (7.2) and the integration of the energy system with the European grid (9.1, 9.4). • The article points out Lithuania's collaboration with other European countries and its integration into the broader European energy market (17.7), essential for achieving the national energy independence strategy.
[52]	• The authors present energy security in the context of the availability and affordability of energy by analyzing energy prices for medium-sized industrial users (7.1), while improving energy intensity and efficiency in the BSR, touching target 7.3 and 13.2.
[56,57]	• The articles explore the role of LNG as a transition from fossil fuels and the long-term goal of increasing the share of renewables in the energy mix and characterizes this infrastructure as a way of enhancing energy security for the BSR and all EU-27 (7.1, 7.2, 9.b). • The articles stress the importance of international cooperation and partnerships in achieving energy security and sustainability (17.7).
[58]	• By assessing energy security from both traditional and sustainable perspectives, the study underscores the need for consistent, secure, and increased energy supplies at reasonable prices (7.1, 7.3)

When it comes to ES, it is noticeable that long-due Russian energy dependency concerns obliged not only Lithuania, but the entirety of Europe, to commit even more to the development of alternative energy sources for gas and other fossil fuels, and to increase the global rate of improvement in EE. The analyzed literature shows a positive response in international cooperations and partnerships within Member States, which expands the interconnection of EE, RE, and ES beyond an environmental and economic perspective.

5. Discussion

This review of Lithuania's energy policies and their alignment with the Sustainable Development Goals showcases the progress of the RES sector and its impact on the country's energy efficiency goals. The findings indicate strong adherence to SDGs 7, 9, 11, 13, and 17, emphasizing the nation's commitment to fulfill the local and international energy and climate change targets contained in the NEIS, NECP and NPP. While the reviewed studies provide comprehensive data on the increase in renewable energy consumption and improvements in energy efficiency, many of the studies lack implementation barrier analysis, which could offer deeper insights into long-term impacts, and they could benefit from a more detailed exploration of specific policy recommendations and strategies to address the identified challenges. It can also be noticed from the studies that provide insights into the potential for energy savings in Lithuanian residential buildings and the effectiveness of current policies, that the measures and policies in this area could be enhanced by incorporating a more detailed analysis of the barriers to the adoption of energy-saving measures by households, including financial constraints, lack of information, and behavioral factors. They could also benefit from more conclusive evidence through the inclusion of surveys that measure citizens' knowledge of energy-efficient technologies. A weakness encountered is that the reliance on existing data sources may limit the ability to capture real-time changes in building stocks and energy efficiency measures, potentially affecting the accuracy of projections. Future research could expand on the integration of renewable energy sources with energy efficiency measures to provide a more rounded approach to achieving SDG 7 and an analysis of accessibility for the population regarding economic incentives and subsidies for citizens to upgrade their households' energy class to A, A+, or A++.

Although the progress made in Lithuania in reducing energy intensity in the building sector is significant, the sector-specific analysis found in the literature suggests that targeted interventions in other sectors like transportation and industry could produce further substantial energy savings. The studied literature reveals that it would be beneficial for future studies addressing energy policies implementation to turn their attention to the impact of emerging technologies and innovation, for example, in the manufacturing and production sectors, for energy efficiency and energy intensity improvement and subsequent GHG emissions reduction. For instance, the studied case of Lithuania–Bulgaria climate change mitigation policies revealed that the implementation of RESs to achieve emission reductions translated into better results on improving EE than focusing on switching from coal to natural gas. Yet, it is important to consider that results at the country level vary significantly depending on specific national policies and their implementation approaches. According to the perceptions obtained from stakeholders interviewed during the surveys, results in the national energy policies progress could be more accurate if there were more monitoring strategies, like real-time measurement of energy use. Some of the feedback from the experts pointed out that many regulations are measured from an ISO standards perspective that does not really consider changes in energy intensity, and that companies can change their consumption behaviors, possibly leading to almost instantaneous changes in consumption patterns, for example, reduced energy waste on the user's side.

Bearing in mind that the practical implications for policymakers include the necessity of supporting renewable energy initiatives and integrating climate change measures into national strategies, while allowing flexibility to adapt to regulations and technological

changes, and promoting collaboration between all stakeholders, further perceptions and recommendations obtained from the survey are listed below:

- While Lithuanian energy policies are effective in promoting sustainable energy development thanks to their strong promotion of full speed RES development, there is a lack of communication with society and businesses. In both public and private sectors, there is a need for a more systematic approach for policy implementation that includes educational programs and transparent communication.
- Energy policies affect operations and strategic planning in all sectors, especially the energy generation and supply sector. Perceptions from these stakeholders include the challenges associated with planning and operating while legislation changes continuously, and with informing their clients and users about those changes while trying to fulfill their needs. They highlight the necessity of obtaining feedback from the end users regarding changes, and once again consider relevant stronger educational and information campaigns carried out by relevant ministries and local governments.
- Examining the energy sector and the development of RESs, interviewees consider that another main barrier is the acceptance of land and infrastructure documentation, as bureaucratic procedures can be exhausting and difficult to interpret.
- Moreover, they noted that other energy sectors, such as transport and industry, are very sensitive to prices. There appears to be a lack of incentives in these sectors for reducing their GHG emissions, aside from monetary incentives for purchasing electric vehicles (EVs) and installing charging stations. Hence, policies must be more flexible and adaptable to avoid business bankruptcies.
- From the public sector perspective, there are concerns from municipalities regarding financial limitations. An example provided by one respondent is that municipalities are forced to use more RESs and reduce GHG emissions, but at the same time the offered loans are not enough to cover the implementation of green projects. The approach to financial capital should be easier and more focused on direct GHG emission savings' results.
- At the EU level, referring to energy efficiency directives, respondents from the private sector consider policymakers to lack flexibility in interpreting the regulations or directive aims designed to achieve the best results in each country. The suggestion of promoting the collaboration between ministries and energy supply businesses, along with academic researchers, should help a lot to show the real effects or impacts of political measures. This will help to create flexibility and to provide feedback for the EC.

In conclusion, Lithuania's energy policies significantly contribute to achieving the SDGs, promoting global sustainability and climate action. The positive correlation between renewable energy adoption and enhanced energy security underscores the importance of continuing these efforts and achieving energy independence. Future research should focus on the socio-economic impacts of energy transitions, ensuring that all societal sectors benefit from these policies, for which it is fundamental to strengthen communication and educational campaigns and develop more approachable RES infrastructure.

6. Conclusions

Lithuania has made significant advances in achieving its targets under the National Energy Independence Strategy and National Energy and Climate Plan, described in Table 1. By 2022, the country's net GHG emissions were reported to be reduced by 69.3%, compared to 1990 levels, while the GHG emissions in the EU ETS sectors decreased by 55.1% compared to the baseline year of 2005. Referring to the non-ETS sectors—namely transport, agriculture, waste, small industry, and buildings—GHG emissions were approximately 14.2 $MtCO_2eq$, of which the transport sector was the biggest contributor with emissions reaching 6 $MtCO_2eq$. Projections indicate that emissions reduction in the non-ETS sectors can reach up to 15% versus 2005 levels by 2030 if existing measures are adhered to [12,29,59].

One of the most notable achievements is Lithuania's substantial increase in renewable energy capacity, particularly from wind and solar sources, helping the country move closer to its 45% renewable energy target by 2030. According to the country's official statistics portal, the consumption of wind energy, hydro-energy, ambient heat (renewable), and solar energy by 2022 was 5445 Terajoules (TJ), 1672 TJ, 2649 TJ, and 1232 TJ, respectively [60]. By the same year, the share of RESs in gross final energy consumption was reported to be 32.7% and the use of RESs in transport accounted for 6.7% (6.5% from biofuels and 0.2% from electricity) [61]. While the achievements for the share of RESs in final energy consumption are promising and in line with the target, the share of RESs in the transport sector seems to be falling behind the expected results, which were set to be 10% by 2022 and at least 15% by 2030 [62]. Reports indicate that the primary and final energy consumption in Lithuania for the year 2022, in Mtoe, was 6.43 and 5.33, respectively [13,59]. To achieve a PEC of 5.4 Mtoe and FEC of 4.5 Mtoe by 2030, Lithuania relies on efforts to promote the renovation of residential and public buildings and to develop industries that are both low in energy intensity and highly efficient, as well as to improve the transport sector energy consumption by upgrading to an efficient public system and overall fleet of vehicles, optimizing the road infrastructure and increasing taxes on diesel, gasoline, and liquefied petroleum gas [10,29].

Lithuania's efforts to fulfill the NEIS and NECP targets are also in line with the European Union's climate objectives and Sustainable Development Goals (SDGs), particularly SDG 7 and SDG 13. However, several challenges remain. Here are some issues identified by the authors in the studied literature, along with their insights into what needs to be carried out to achieve the goals in a timely manner:

- High Dependence on Biomass and Fossil Fuels (SDG 7, SDG 13). Although Lithuania has increased its renewable energy share, a significant portion comes from biomass, which can contribute to air pollution and carbon emissions [63]. Additionally, Lithuania still provides subsidies for fossil fuels and has not implemented a carbon tax [7,10], which could slow its progress towards a low-carbon economy; hence, implementing carbon taxes is a strong recommendation for policymakers. Furthermore, transport sector emissions continue to be significantly high, wherefore it is fundamental to develop an affordable and efficient transport system [64]. Some measures to facilitate the latter could include lower taxes for EV vehicles and limiting the mobility in congested areas of vehicles that run on fossil fuels.
- Energy Efficiency Gaps (SDG 7, SDG 9). Despite advances in energy efficiency, there is still potential for improvement, especially in older building infrastructure and industrial processes. Limited funding for energy efficiency retrofits and high upfront costs for sustainable technology adoption create barriers to further progress in this area, so it is necessary to speed up the modernization of the building stock as well as improve educational campaigns for citizens to understand the importance of this measure.
- Limited Investment in Green R&D (SDG 9, SDG 13). While Lithuania has made some investments in sustainable technologies, the funding for research and development (R&D) in green innovation remains relatively low, as it was also stated in the discussion section from the survey participants insights. Increased investment in environmental R&D could drive innovation in renewable energy, energy efficiency, and energy independence.
- Public Awareness and Engagement (SDG 13, SDG 12). Although environmental awareness is growing, there is still a need for greater public understanding of climate change and sustainable practices. As stated in the discussion section, engaging citizens in sustainable actions and increasing environmental education can be vital for achieving behavioral shifts toward more sustainable consumption patterns.
- Insufficient CO_2 Pricing Mechanisms (SDG 13). Without a carbon tax or stronger emissions trading mechanisms, Lithuania lacks a key economic tool to effectively price carbon emissions and encourage emission reductions across sectors [7]. Introducing

CO_2 pricing could help align sectoral emissions reductions with national and EU climate targets.

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Appendix A

Survey Questions:

1. How effective do you think current energy policies are in promoting sustainable energy development in Lithuania?
2. How do current energy policies affect your business operations and strategic planning in the energy sector?
3. What role do you think government policies play in encouraging innovation and investment in renewable energy technologies?
4. How can collaboration between the public and private sectors be improved to achieve better energy outcomes?
5. Are there any areas or issues you believe do not adequately address current energy policies? If so, what are they?
6. What are the primary challenges your company faces in the energy market, and how can policy changes help mitigate these challenges?
7. What changes or new policies do you think are necessary to improve Lithuania's RES sector in the next decade?

References

1. U.S. Environmental Protection Agency. Climate Change Indicators: Weather and Climate. Available online: https://www.epa.gov/climate-indicators/weather-climate (accessed on 15 April 2024).
2. Kuh, K.F. The law of climate change mitigation: An overview. *Encycl. Anthr.* **2018**, *2*, 505–510.
3. European Climate Foundation (ECF). Climate Change: Implications for the Energy Sector. Available online: https://www.worldenergy.org/assets/images/imported/2014/06/Climate-Change-Implications-for-the-Energy-Sector-Summary-from-IPCC-AR5-2014-Full-report.pdf (accessed on 7 August 2024).
4. Thorne, P.W.; Trisos, C.; Romero, J.; Aldunce, P.; Barrett, K.; Blanco, G.; Cheung, W.W.L.; Connors, S.; Denton, F.; Diongue-Niang, A.; et al. *IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Core Writing Team, Lee, H., Romero, J., Eds.; IPCC: Geneva, Switzerland, 2023. Available online: https://www.ipcc.ch/report/ar6/syr/ (accessed on 16 March 2024).
5. Tiseo, I. GHG Emissions in the EU—Statistics & Facts. Available online: https://www.statista.com/topics/4958/emissions-in-the-european-union/#topicOverview (accessed on 23 February 2024).
6. European Commission. Communication from the Commission to The European Parliament, The Council, The European Economic and Social Committee and The Committee of the Regions; Brussels, 2020. Stepping Up Europe's 2030 Climate Ambition. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52020DC0562 (accessed on 28 February 2024).
7. OECD. *Reform Options for Lithuanian Climate Neutrality by 2050*; OECD Publishing: Paris, France, 2023. [CrossRef]
8. Ministry of Environment of the Republic of Lithuania. Lithuania's Eight National Communication and Fifth Biennial Report. 2022. Available online: https://am.lrv.lt/uploads/am/documents/files/KLIMATO%20KAITA/%C5%A0ESD%20apskaitos%20ir%20kt%20ataskaitos/8th%20NC%20and%205th%20BR_20230105%20final.pdf (accessed on 14 March 2024).
9. Janeliūnas, T. Energy Without Russia. The Consequences of the Ukraine War and the EU Sanctions on the Energy Sector in Europe. 2023. Available online: https://library.fes.de/pdf-files/bueros/budapest/20409.pdf (accessed on 6 May 2024).
10. Odyssee-Mure. Energy Efficiency Trends and Policies—Lithuania Profile. Available online: https://www.odyssee-mure.eu/publications/efficiency-trends-policies-profiles/lithuania.html (accessed on 3 May 2024).

11. Enerdata. Lithuania Energy Information. Available online: https://www.enerdata.net/estore/energy-market/lithuania/ (accessed on 3 May 2024).
12. European Commission. Climate Action Progress Report—Country Profile Lithuania. 2023. Available online: https://climate.ec.europa.eu/document/download/cfbb0021-bee8-4ad3-bb68-e5d7560ba43f_en?filename=lt_2023_factsheet_en.pdf (accessed on 3 May 2024).
13. European Commission—The Directorate-General for Energy. National Energy and Climate Action Plan of the Republic of Lithuania for 2021–2030. Available online: https://energy.ec.europa.eu/system/files/2022-08/lt_final_necp_main_en.pdf (accessed on 12 March 2024).
14. International Energy Agency. Energy and Climate Are Inextricably Linked. Available online: https://www.iea.org/topics/climate-change (accessed on 3 May 2024).
15. UN General Assembly. Transforming Our World: The 2030 Agenda for Sustainable Development A/RES/70/1. 2015. Available online: https://www.refworld.org/legal/resolution/unga/2015/en/111816 (accessed on 12 March 2024).
16. United Nations. SDG 7. Available online: https://sdgs.un.org/goals/goal7 (accessed on 12 March 2024).
17. United Nations. SDG 13. Available online: https://sdgs.un.org/goals/goal13 (accessed on 16 March 2024).
18. Šneiderienė, A.; Ruginė, H. Green technologies development in The European Union and Lithuania. *Manag. Theory Stud. Rural. Bus. Infrastruct. Dev.* **2019**, *41*, 249–263. [CrossRef]
19. United Nations. SDG 11. Available online: https://sdgs.un.org/goals/goal11 (accessed on 3 May 2024).
20. United Nations. SDG 9. Available online: https://sdgs.un.org/goals/goal9 (accessed on 3 May 2024).
21. Climate Change Knowledge Portal. Lithuania—Current Climate: Climatology. Available online: https://climateknowledgeportal.worldbank.org/country/lithuania/climate-data-historical (accessed on 10 March 2024).
22. Climate Change Knowledge Portal. Lithuania—Climate Change Overview. Available online: https://climateknowledgeportal.worldbank.org/country/lithuania (accessed on 10 March 2024).
23. Climate Adapt. Information on National Adaptation Actions Reported Under the Governance Regulation. Available online: https://climate-adapt.eea.europa.eu/en/countries-regions/countries/lithuania (accessed on 8 May 2024).
24. Rimkus, E.; Briede, A.; Jaagus, J.; Stonevicius, E.; Kilpys, J.; Viru, B. Snow-cover regime in Lithuania, Latvia and Estonia and its relationship to climatic and geographical factors in 1961–2015. *Boreal Env.* **2018**, *23*, 193–208.
25. The Ministry of Environment of the Republic of Lithuania. Lithuania's Greenhouse Gas Inventory Report 2022. Available online: https://am.lrv.lt/uploads/am/documents/files/Klimato_kaita/NIR_2022%2003%2015%20FINAL.pdf (accessed on 10 March 2024).
26. Jonynas, R.; Puida, E.; Poškas, R.; Paukštaitis, L.; Jouhara, H.; Gudzinskas, J.; Miliauskas, G.; Lukoševičius, V. Renewables for District Heating: The Case of Lithuania. *Energy* **2020**, *211*, 119064. [CrossRef]
27. Liselotte, J. BRIEFING EU. Progress on Climate Action-How Are the Member States Doing? Available online: https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/698844/EPRS_BRI(2021)698844_EN.pdf (accessed on 8 May 2024).
28. European Commission. Climate Action Progress Report—Country Profile Lithuania. 2022. Available online: https://climate.ec.europa.eu/eu-action/climate-strategies-targets/progress-climate-action_en (accessed on 28 February 2024).
29. IEA. *Lithuania 2021 Energy Policy Review*; IEA Energy Policy Reviews; OECD Publishing: Paris, France, 2021. [CrossRef]
30. Al-Marri, W.; Al-Habaibeh, A.; Watkins, M. An Investigation into Domestic Energy Consumption Behaviour and Public Awareness of Renewable Energy in Qatar. *Sustain. Cities Soc.* **2018**, *41*, 639–646. [CrossRef]
31. European Commission. *A Policy Framework for Climate and Energy in the Period from 2020 to 2030*; European Commission: Brussels, Belgium, 2014.
32. Eurostat Glossary: Energy Intensity. 2020. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Energy_intensity (accessed on 10 March 2024).
33. Ringel, M. Tele-Coupling Energy Efficiency Polices in Europe: Showcasing the German Governance Arrangements. *Sustainability* **2018**, *10*, 1754. [CrossRef]
34. National Control Commission for Prices and Energy. Annual Report on Electricity and Natural Gas Markets of the Republic of Lithuania to the European Commission. 2012. Available online: https://www.regula.lt/en/SiteAssets/ncc-reports/NCC-report-2012.pdf (accessed on 17 May 2024).
35. Baležentis, A.; Baležentis, T.; Streimikiene, D. The Energy Intensity in Lithuania during 1995–2009: A LMDI Approach. *Energy Policy* **2011**, *39*, 7322–7334. [CrossRef]
36. European Commission. *Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on Energy Efficiency and Amending Regulation (EU) 2023/955 (Recast) (Text with EEA Relevance)*; European Commission: Brussels, Belgium, 2023.
37. Streimikiene, D.; Volochovic, A.; Simanaviciene, Z. Comparative Assessment of Policies Targeting Energy Use Efficiency in Lithuania. *Renew. Sustain. Energy Rev.* **2012**, *16*, 3613–3620. [CrossRef]
38. Simanaviciene, Z.; Volochovic, A.; Simanavicius, A. Analysis of Energy Efficiency Improvement and Climate Change Mitigation Policy in Lithuania. *WIT Trans. Ecol. Environ.* **2014**, *186*, 739–749.
39. Toleikyte, A.; Kranzl, L.; Müller, A. Cost Curves of Energy Efficiency Investments in Buildings—Methodologies and a Case Study of Lithuania. *Energy Policy* **2018**, *115*, 148–157. [CrossRef]
40. European Commission. Long-Term Renovation Strategy of Lithuania. Available online: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/long-term-renovation-strategies_en (accessed on 8 August 2024).

41. Miskinis, V.; Galinis, A.; Konstantinaviciute, I.; Lekavicius, V.; Neniskis, E. Comparative Analysis of Energy Efficiency Trends and Driving Factors in the Baltic States. *Energy Strategy Rev.* **2020**, *30*, 100514. [CrossRef]
42. Miskinis, V.; Galinis, A.; Bobinaite, V.; Konstantinaviciute, I.; Neniskis, E. Impact of Key Drivers on Energy Intensity and GHG Emissions in Manufacturing in the Baltic States. *Sustainability* **2023**, *15*, 3330. [CrossRef]
43. IRENA. *Synergies Between Renewable Energy and Energy Efficiency: A Working Paper Based on Remap*; International Renewable Energy Agency (IRENA): Abu Dhabi, United Arab Emirates, 2017. Available online: www.irena.org/remap (accessed on 5 November 2024).
44. Mikalauskiene, A.; Štreimikis, J.; Mikalauskas, I.; Stankūniene, G.; Dapkus, R. Comparative Assessment of Climate Change Mitigation Policies in Fuel Combustion Sector of Lithuania and Bulgaria. *Energies* **2019**, *12*, 529. [CrossRef]
45. Bobinaite, V.; Juozapaviciene, A.; Konstantinaviciute, I. Assessment of Causality Relationship between Renewable Energy Consumption and Economic Growth in Lithuania. *Eng. Econ.* **2011**, *22*, 510–518. [CrossRef]
46. Gaigalis, V.; Katinas, V. Analysis of the Renewable Energy Implementation and Prediction Prospects in Compliance with the EU Policy: A Case of Lithuania. *Renew Energy* **2020**, *151*, 1016–1027. [CrossRef]
47. Miškinis, V.; Galinis, A.; Konstantinavičiūtė, I.; Lekavičius, V.; Neniškis, E. The Role of Renewable Energy Sources in Dynamics of Energy-Related GHG Emissions in the Baltic States. *Sustainability* **2021**, *13*, 10215. [CrossRef]
48. Streimikiene, D. Assessment of Progress Towards 20-20-20 Targets: Evidence from Baltic States. *Contemp. Econ.* **2022**, *16*, 135–150. [CrossRef]
49. Žičkienė, A.; Morkunas, M.; Volkov, A.; Balezentis, T.; Streimikiene, D.; Siksnelyte-butkiene, I. Sustainable Energy Development and Climate Change Mitigation at the Local Level through the Lens of Renewable Energy: Evidence from Lithuanian Case Study. *Energies* **2022**, *15*, 980. [CrossRef]
50. Rodríguez-Fernández, L.; Fernández Carvajal, A.B.; Ruiz-Gómez, L.M. Evolution of European Union's Energy Security in Gas Supply during Russia–Ukraine Gas Crises (2006–2009). *Energy Strategy Rev.* **2020**, *30*, 100518. [CrossRef]
51. Sattich, T.; Morgan, R.; Moe, E. Searching for Energy Independence, Finding Renewables? Energy Security Perceptions and Renewable Energy Policy in Lithuania. *Polit. Geogr.* **2022**, *96*, 102656. [CrossRef]
52. Zeng, S.; Streimikiene, D.; Baležentis, T. Review of and Comparative Assessment of Energy Security in Baltic States. *Renew. Sustain. Energy Rev.* **2017**, *76*, 185–192. [CrossRef]
53. Maigre, M.; International Center for Defense and Security. Energy Security Concerns of the Baltic States. Available online: https://icds.ee/en/energy-security-concerns-of-the-baltic-states/ (accessed on 14 March 2024).
54. Katinas, V.; Markevicius, A.; Perednis, E.; Savickas, J. Sustainable Energy Development—Lithuania's Way to Energy Supply Security and Energetics Independence. *Renew. Sustain. Energy Rev.* **2014**, *30*, 420–428. [CrossRef]
55. Stang, G.; Bechev, D.; Butler, E.; Nowak, Z.; Tagliapietra, S.; Reports, K.W.; Missiroli, A. *Securing the Energy Union: Five Pillars and Five Regions*; EU Institute for Security Studies: Paris, France, 2017; Volume 32.
56. Gritsenko, D. Explaining Choices in Energy Infrastructure Development as a Network of Adjacent Action Situations: The Case of LNG in the Baltic Sea Region. *Energy Policy* **2018**, *112*, 74–83. [CrossRef]
57. Gritz, A.; Wolff, G. Gas and Energy Security in Germany and Central and Eastern Europe. *Energy Policy* **2024**, *184*, 113885. [CrossRef]
58. Brodny, J.; Tutak, M. Assessing the Energy Security of European Union Countries from Two Perspectives—A New Integrated Approach Based on MCDM Methods. *Appl. Energy* **2023**, *347*, 121443. [CrossRef]
59. Čižikienė, G.; Norvydas, T. Modelling Activity Report on the Achievement of Indicative Trajectories in 2022, 2025 and 2027. Available online: https://klimatokaita.lt/umbraco/Surface/TemplateSurface/DisplayFile/54513 (accessed on 3 November 2024).
60. Official Statistics Portal. Environment, Agriculture and Energy in Lithuania (Edition 2023)—Renewable Energy Resources. Available online: https://osp.stat.gov.lt/lietuvos-aplinka-zemes-ukis-ir-energetika-2023/energetika/atsinaujinantys-energijos-istekliai (accessed on 2 November 2024).
61. National Audit Office of Lithuania. Implementation of the Energy Independence Targets in the Transport Sector. Available online: https://www.valstybeskontrole.lt/EN/Post/17837/greenhouse-gas-emissions-from-transport-are-falling-too-slowly (accessed on 2 November 2024).
62. Delfi.en; Vaišvilaitė-Braziulienė, J. Lithuania Among EU Countries with Lowest Share of Renewables in Transport. Available online: https://www.delfi.lt/en/business/lithuania-among-eu-countries-with-lowest-share-of-renewables-in-transport-95931019 (accessed on 3 November 2024).
63. Varnagirytė-Kabašinskienė, I.; Lukminė, D.; Mizaras, S.; Beniušienė, L.; Armolaitis, K. Lithuanian Forest Biomass Resources: Legal, Economic and Ecological Aspects of Their Use and Potential. *Energy Sustain. Soc.* **2019**, *9*, 41. [CrossRef]
64. The Seimas of the Republic of Lithuania Resolution Approving the National Climate Change Agenda. Available online: https://e-seimas.lrs.lt/portal/legalActPrint/lt?jfwid=-56ckr0gcc&documentId=219a2632a6b311ecaf79c2120caf5094&category=TAD (accessed on 3 November 2024).

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Development of Semi-Mountainous and Mountainous Areas: Design of Trail Paths, Optimal Spatial Distribution of Trail Facilities, and Trail Ranking via MCDM-VIKOR Method

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Abstract: This study proposes a sustainable ecotourism framework for the development of semi-mountain and mountain regions of Paiko in Greece, focusing on the strategic design and ranking of trail paths using the multi-criteria decision-making (MCDM) VIKOR method. Aiming to balance environmental conservation with economic benefits, we designed 19 trails paths and allocated signage for resting and recreation facilities. The trail paths were assessed based on criteria such as length, difficulty, scenic appeal, and accessibility. This approach identified key trails that combine scenic beauty with infrastructure suitable for a broad range of visitors, thereby enhancing sustainable tourism appeal. Stakeholder engagement was integral to shaping the trail network, ensuring that the selected paths reflect local values and priorities. This study highlights how the VIKOR method can optimize resource allocation by ranking trails according to their environmental and visitor-centered attributes, supporting regional economic growth through ecotourism. This framework offers a replicable model for other mountainous regions seeking to harness ecotourism's potential while preserving natural ecosystems. The findings demonstrate the capacity of well-planned trail networks to attract nature-based tourism, stimulate local economies, and respond to the rising post-pandemic interest in outdoor recreation, while promoting long-term conservation efforts. This approach offers a replicable model for the sustainable development of mountainous and semi-mountainous areas in Greece and beyond.

Keywords: strategic planning; decision making; forest operations; nature-based solution; multi-criteria evaluation; sustainable tourism; local communities; natural environment

1. Introduction

Semi-mountainous and mountainous regions present significant opportunities for both tourism and sustainable development [1]. The distinct ecological value of these regions makes them essential for the implementation of conservation strategies aimed at preserving biodiversity and maintaining ecosystem services [2,3]. Simultaneously, their natural beauty and cultural heritage offer immense potential for sustainable tourism practices that can generate economic benefits for local communities while minimizing environmental impacts. As such, balancing conservation efforts with tourism development in these areas is crucial to ensuring long-term ecological integrity and socio-economic growth [4–6].

In Mediterranean countries such as Greece, the development of semi-mountainous and mountainous regions plays a crucial role in promoting sustainable growth, particularly given that these areas are not typically associated with mass cultural tourism, archaeological sites, or coastal tourism [7,8]. The focus on these regions shifts towards their distinct natural environment and the opportunity they provide for connecting with nature,

which sets them apart from other tourism-driven areas. In Greece, mountainous areas hold significant advantages in terms of their unique landscapes, biodiversity, and the authentic experiences they offer [9]. These qualities make them valuable assets for developing alternative forms of tourism, such as ecotourism and adventure tourism, which can support both the preservation of natural habitats and the economic development of local communities [10–12]. Leveraging these natural advantages allows for a balanced approach to regional development, enhancing the sustainability of these areas while promoting their economic viability through carefully managed tourism strategies [13].

In recent years, the demand for outdoor activities in natural environments has seen a notable increase, particularly in the aftermath of the COVID-19 pandemic [14,15]. This shift can be attributed to a growing recognition of the physical and mental health benefits associated with spending time in nature [16]. Outdoor activities such as hiking, cycling, and nature exploration provide opportunities for exercise, stress relief, and emotional well-being, which have become even more critical as people seek safe and rejuvenating ways to escape the pressures of urban life [17]. The pandemic emphasized the importance of open spaces and natural environments as sanctuaries for mental health, with many individuals turning to nature for relaxation and recovery [18]. As a result, the interest in engaging with nature has become a key factor in promoting sustainable tourism and the development of rural and natural areas, as it aligns with both public health and ecological conservation goals.

Trails can serve as a vital tool in promoting the development of semi-mountainous and mountainous areas. Establishing well-planned trail networks offers an alternative avenue for attracting tourists while simultaneously improving the quality of life for local residents. These trails not only provide access to nature but also encourage outdoor activities such as hiking, trekking, and cycling, which have seen a surge in popularity in recent years [19]. As interest in outdoor experiences continues to grow, the demand for well-structured and safe trails becomes increasingly important [20]. Properly designed trail systems enhance the visitor experience by offering safe, enjoyable routes that showcase the natural beauty of the region, while also ensuring the protection and preservation of the environment [21]. Furthermore, such developments can contribute to the local economy by increasing tourist footfall, supporting small businesses, and fostering a deeper connection between people and nature [22,23].

The development of trails has evolved beyond the narrow focus of catering solely to individuals with high levels of physical fitness and now extends to a much broader audience. Modern trail networks are being designed to be accessible to all social groups and ages, regardless of physical ability [24]. This inclusive approach allows more people to engage with nature and outdoor activities, promoting health and well-being for a wider population. By offering different levels of difficulty and ensuring that trails are safe and accessible, these paths can accommodate everyone, from families with young children [25] to older adults and people with mobility challenges [26,27]. This shift not only democratizes access to natural environments but also enhances social cohesion, as outdoor spaces become shared spaces for recreation, education, and relaxation. Moreover, creating inclusive trail systems can further stimulate local tourism, as more diverse groups of visitors are encouraged to explore these areas, benefiting both the local community and the regional economy [28,29].

A fundamental prerequisite for the effective operation of a trail network is the inclusion of essential infrastructure such as signage and rest areas. These technical features are crucial for ensuring the safety and comfort of trail users [30]. Clear and consistent signage helps guide visitors along the routes, providing important information about distances, difficulty levels, and potential hazards, which contributes to an overall sense of security [31]. Rest areas offer places for relaxation and recovery, making the trails more accessible to a broader range of users, regardless of physical ability. Additionally, providing accurate and easily understandable information enhances user experience by promoting awareness of the natural environment and encouraging responsible behavior [32]. Properly equipped

trails not only foster a safer and more enjoyable outdoor experience but also support the sustainable development of the area by ensuring that users feel informed and confident as they explore [33,34].

Numerous studies have applied diverse methodologies to develop and evaluate trail systems in mountainous and rural areas worldwide [35,36]. For instance, research in European mountain regions highlights the use of multi-criteria decision-making (MCDM) frameworks to balance conservation with tourism development effectively [1]. Similar methodologies have been implemented in other mountainous areas, in order to prioritize trails based on accessibility, environmental impact, and visitor experience [37,38]. This view emphasizes adaptive approaches in trail network design that integrate stakeholder engagement and ecological assessments, ensuring that trail development aligns with both conservation goals and recreational demand [39]. These global insights offer valuable perspectives on leveraging advanced decision-making tools and inclusive design processes for sustainable trail development across diverse landscapes.

This study seeks to address the challenges of trail planning and facility distribution by employing advanced decision-making methods, contributing to both sustainable tourism and regional development. The ultimate goal is to establish a comprehensive decision-making system that, by utilizing spatial analysis tools, will create a trail network that caters to all types of users and acts as a catalyst for the development of mountainous and semi-mountainous areas. In addition to this, this study presents the application of the VIKOR method for ranking the trails. This ranking process can serve as an important tool for optimizing resource allocation and prioritizing investments in trail infrastructure, ensuring that the most suitable routes are developed based on various user needs and environmental considerations.

Recent advances in multi-criteria decision-making (MCDM) techniques, such as the VIKOR method [40–42], offer an objective framework for evaluating and ranking trail paths and associated facilities. The VIKOR method, known for its ability to integrate conflicting criteria and provide a compromise solution, has been widely applied in areas such as urban planning, transportation, and environmental management. By applying this method to trail planning, this research provides a structured approach to decision-making that balances various factors like environmental impact, user accessibility, and economic potential, ultimately promoting more efficient and sustainable trail network development.

The research offers a comprehensive approach to road and trail network planning that prioritizes eco-tourism and sustainable development in mountainous and semi-mountainous areas. By balancing accessibility with environmental stewardship, the proposed network serves not only as a tool for economic revitalization but also as a model for ecological preservation and community engagement. The design criteria and methodologies applied here can be adapted to similar regions facing the dual challenge of promoting tourism while conserving natural landscapes, making this framework a valuable reference for planners and stakeholders aiming for sustainable regional development.

2. Materials and Methods

2.1. Research Area

The present research was conducted in the forest complex of Mount Paiko, which is located within the administrative boundaries of the Municipality of Pella, Regional District of Pella and the Municipality of Paionia, Regional District of Kilkis, in the Region of Central Macedonia, Greece. The core area for this study was carefully selected, covering a total surface area of 69.79 km^2, as depicted in Figure 1. This entire region is classified as public forest land, and its supervision and management fall under the jurisdiction of the Forest Directorate of Pella, which operates under the Ministry of Environment and Energy of Greece. This designation ensures that the area is subject to government regulations focused on sustainable forest management and conservation.

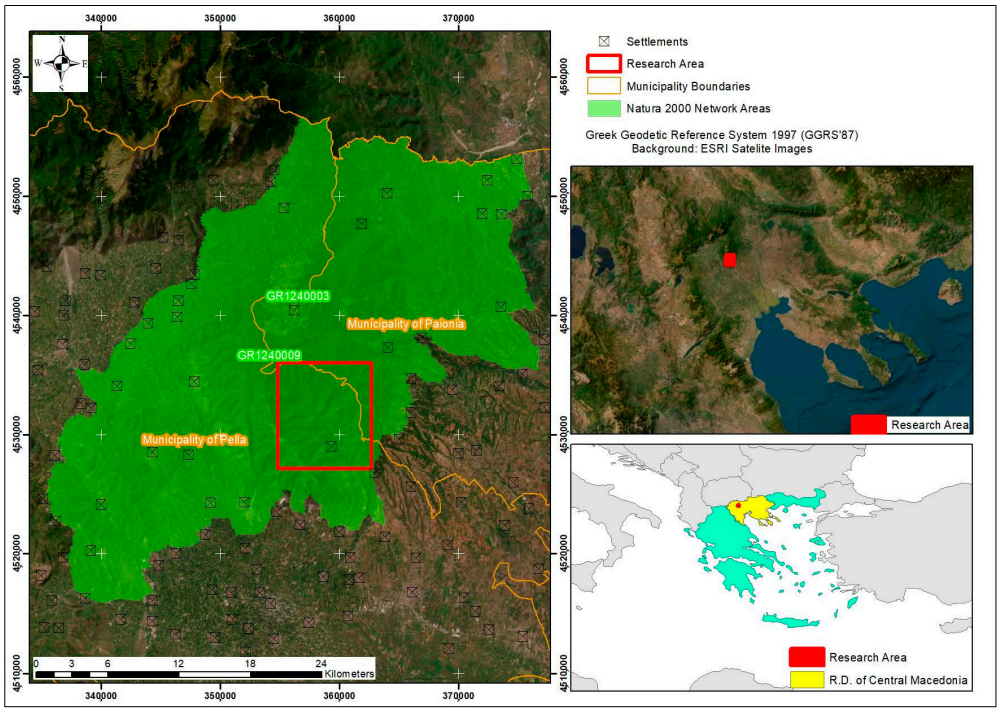


Figure 1. Location map of the research area.

Mount Paiko is part of the Natura 2000 network, specifically under the designations GR1240009—Oros Paiko, Stena Apsalou Kai Moglenitsas, and GR1240003—Oros Paiko. The inclusion of this area in the Natura 2000 network highlights its ecological significance, as the region supports a range of protected species and habitats. This classification emphasizes the importance of preserving the area's biodiversity and managing its natural resources sustainably. The unique ecosystems found in this mountainous area provide valuable environmental services, further justifying its protected status and the focus of this research.

As a semi-mountainous and mountainous area, Mount Paiko serves as an exemplary case of natural beauty and ecological value. Its diverse landscapes and rich biodiversity make it a major attraction for both local residents and visitors from across Greece. The Mount Paiko is a protected natural area administered collaboratively by the Natural Environment & Climate Change Agency and the Municipality of Pella. While it is appreciated for its natural beauty and biodiversity, Mount Paiko is managed primarily for conservation and sustainable recreation rather than commercial tourism. The region is not a profit-driven forest park but instead a designated site for low-impact outdoor activities like hiking and nature exploration, aligning with its role within the Natura 2000 network. This management approach ensures that the ecological and cultural significance of Mount Paiko is preserved while providing controlled access to visitors, supporting sustainable tourism practices and reinforcing its role as a conservation area.

2.2. Trail Path and Facilities Design Specifications

The technical specifications for the design, signage, construction, and maintenance of hiking and trekking trails in Greece are defined by Ministerial Decision 151344/165 (Greek Government Gazette 206/B/30-1-2017). Through the implementation of this decision, Greece has established a comprehensive framework for the creation of trails and hiking routes. According to this framework, mountain and hiking trails are recognized as important components of the country's natural and cultural heritage, offering visitors the opportunity to explore landscapes and attractions in a sustainable manner. These trails are developed based on specific technical criteria and are categorized according to their purpose and the region they traverse.

The primary objective of these trails is to facilitate access to natural and cultural landmarks, while also improving communication in remote areas. Moreover, they promote forest recreation and ecotourism, supporting the preservation and showcasing of each region's natural and cultural heritage. Trails can pass through various landscapes such as mountainous areas, rivers, lakes, and protected zones, ensuring the conservation of flora and fauna. By doing so, they not only enhance visitor experiences but also contribute to the protection of the environment. The trails are divided into various categories based on their purpose and the areas they traverse. Some of the most significant types include:

- Recreational Trails (E): designed for hikers and nature enthusiasts who wish to explore the natural environment.
- Educational—Thematic Trails (L): aimed at visitors interested in learning about the natural and cultural environment of a specific region.
- Cycling Trails (B): designed for cyclists, featuring specific characteristics for safe and enjoyable cycling experiences.
- Accessible Trails for People with Disabilities (A): trails designed to be accessible to individuals with disabilities.
- Livelihood Trails: used for the daily activities of locals, such as accessing fields and grazing areas.

Rest areas are designed to offer visitors a chance to relax during their hike. These spaces can be created in natural clearings or artificial widenings, typically located near water sources, and equipped with benches and tables made from natural materials. Special attention is given to ensuring accessibility for individuals with disabilities in these areas. Trail signage is crucial for ensuring the safety of hikers and the smooth navigation of routes. It includes directional, informational, location, and warning signs for potential hazards. Each trail must have clear and accurate signage that provides information about the route, difficulty level, and points of interest. The signs are distinguished by shapes and colors, such as diamonds for European trails and rectangles for local route networks. Signage must be highly visible and constructed from materials that can withstand various weather conditions.

The design, construction, and maintenance of trails are subject to specific technical specifications to ensure the safety of hikers and the protection of the natural environment. In every trail planning and maintenance project, local geomorphological characteristics, visitor needs, and environmental constraints are carefully considered. The final construction of the trails must respect the natural harmony and ecological balance of the area, ensuring a sustainable approach to trail development.

2.3. Methodology

Figure 2 outlines the comprehensive steps undertaken for the implementation of the present research. Initially, geospatial data was collected from the area of interest to ensure accurate mapping and trail design. Simultaneously, stakeholder engagement was conducted to identify key points of interest (POIs) and determine the appropriate types of trails based on the needs of the community and visitors. This was followed by the extraction of geometric and technical features necessary for the development of the trail paths. Field measurements were then integrated to guide the detailed design of the trails, ensuring they met technical specifications. Once the paths were designed, efforts were made to define accessibility improvement operations, plan trail signage projects, and allocate rest and seating areas to enhance user experience. Finally, the VIKOR method was applied to rank the trails by determining weighting factors for various criteria, providing a structured approach to optimizing trail development and ensuring a balanced consideration of all relevant factors.

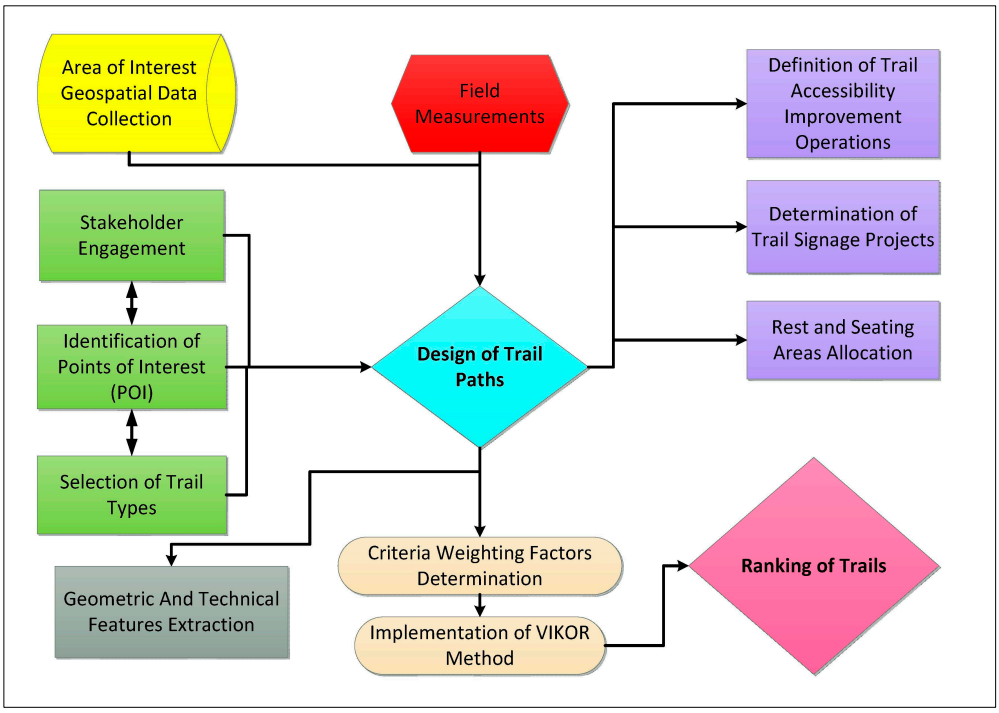


Figure 2. Flowchart of implemented methodology.

2.3.1. Data Collection and Decision Analysis

The first step in the integrated design of the trail path network involved the collection and analysis of all necessary geospatial data. This included the Digital Elevation Model (DEM) of the region, satellite imagery, orthophotos of the wider area, and the hydrographic network. These data sources were crucial for identifying the peaks and generating a detailed slope model of the area, allowing for the identification of steep and challenging sections of the terrain. In accordance with established technical specifications, the trails are required to pass exclusively through public land. To ensure this, spatial data from the Hellenic Cadastre and the Greek Forest Registry were gathered to identify areas where the development of trails is restricted. Furthermore, the road network within the region was digitized to mark key access points, ensuring that the proposed trail system would be easily accessible from existing roads. These preparatory steps were essential for laying the foundation of a trail network that not only meets technical and legal requirements but also aligns with sustainability and accessibility goals.

The geospatial analysis in this study utilized advanced spatial data tools, including ArcGIS Desktop version 10.8 software for high-resolution mapping and trail optimization. Similar to the spatial analysis frameworks in literature [43,44], this study leverages spatial decision-support tools to optimize trail network design, ensuring an environmentally and logistically sound approach to sustainable ecotourism development. The software enabled intricate terrain analysis through its Digital Elevation Model (DEM) features, which facilitated the calculation of slope, elevation, and terrain ruggedness. This allowed for an accurate assessment of each trail segment's difficulty level and suitability for different user groups. Viewshed analysis was employed to evaluate scenic visibility from various points, ensuring optimal placement of rest areas and viewpoints to enhance visitor experience.

The selection of the trails to be developed was carried out with the active involvement of all relevant stakeholders. These included representatives from the regional government, local municipalities, the forestry service, the local mountaineering club, representatives of local communities, as well as citizens who are actively engaged in volunteer work within the area. For the stakeholder engagement component, a structured multi-phase process was adopted. Subsequent workshops and interviews were conducted to gather qualitative insights and preferences, followed by surveys to quantify stakeholder priorities

on trail features, accessibility, and conservation needs. This systematic approach allowed for an integration of both expert and community-based perspectives, enhancing the trail network's alignment with ecological sustainability and visitor accessibility goals.

Feedback from community stakeholders significantly impacted the final trail designs, ensuring the network was both practical and aligned with local values. For instance, community members highlighted specific natural landmarks and culturally important sites, prompting adjustments in trail routes to incorporate access to these points. This input led to the addition of scenic lookouts and rest areas at locations cherished by locals, enhancing both visitor experience and cultural appreciation. Furthermore, residents voiced concerns about accessibility for all age groups, leading to the creation of alternative, less strenuous trail segments alongside more challenging routes. This inclusion of diverse trail options ensured the network was accessible to families, elderly visitors, and individuals with varying fitness levels. Overall, the direct incorporation of local insights created a trail system that reflects and respects the community's unique connection to the landscape.

Through this collaborative process, key points of interest within the study area were identified, which the proposed trail network is intended to highlight and promote. Additionally, the types of trails to be implemented were determined based on the preferences and needs expressed by the local stakeholders. This participatory approach ensured that the trail network not only serves the ecological and recreational objectives but also aligns with the broader vision of regional development and community engagement. By incorporating diverse perspectives, the project aims to create a trail system that supports sustainable tourism, fosters environmental awareness, and enhances the cultural and natural heritage of the region.

2.3.2. Trail Path Design and Trail Facilities Allocation

The design of the trails aimed to highlight the points of interest within the area and to create a multi-level trail network, offering routes of varying difficulty levels. This approach was intended to cater not only to experienced mountaineers but also to a broader audience, including casual hikers and nature enthusiasts.

Once all the necessary data and information had been collected, field measurements were carried out. Geodetic instruments were used to accurately capture the routes, and the collected data was processed using ArcGIS Desktop version 10.8 software. The route design process included the extraction of geometric features, such as the length of each trail, as well as the calculation of maximum and average slopes for both uphill and downhill sections.

Based on these parameters—length, slope, and type of terrain—the trails were classified according to their level of difficulty. The classification system ranged from "Very Easy" and "Easy" to "Medium", "Hard", and "Very Hard". This categorization ensured that the trail network could accommodate a diverse range of users, from beginners seeking leisurely walks to advanced hikers looking for more challenging terrain. By providing this range of options, the trail system enhances accessibility while promoting broader engagement with the natural environment.

The signage system for the trail network included three levels of signage to ensure comprehensive information and guidance for visitors. The first level consisted of central signs, which provided an overview of the entire trail network. These signs displayed essential information, such as the types and difficulty levels of the trails, distances, estimated traversal times, and details about nearby attractions. They were strategically placed at key entry points where visitors accessed the trail network, offering a clear starting point for their journey. The second level of signage consisted of informational signs, placed at appropriate locations along the trails. These signs provided visitors with valuable insights into the region's points of interest, broader contextual information about the surrounding area, and warnings about potential hazards (e.g., falling rocks, steep sections). Additionally, they included reminders to respect the natural environment, encouraging responsible behavior and environmental stewardship among visitors. The final level of signage involved

directional signs, placed approximately every 200 m along the trails. These signs served to inform visitors of their current kilometer position and the remaining distance and time to key destinations. This consistent and clear signage system was designed to enhance the overall trail experience, ensuring visitors felt safe, well-informed, and confident in navigating the network, regardless of their experience level.

A key parameter that was calculated was the determination of accessibility improvement operations. These operations focused on identifying and implementing necessary interventions to enhance the accessibility of the trail network, ensuring that the trails are navigable for a wider range of users. The trail sections were categorized based on vegetation density to guide the necessary clearing and maintenance work. Sections where the vegetation posed minimal challenges to trail accessibility were classified as Level 1. In these areas, only minor clearing was required, which involved trimming branches up to a height of 2.5 m and removing undergrowth. On the other hand, sections where the vegetation was denser and required more thorough maintenance were classified as Level 2. In these areas, more extensive clearing was necessary to ensure safe and unobstructed passage for trail users. By classifying the trails according to vegetation density, the maintenance efforts could be better prioritized and adapted to the specific conditions of each trail section, ensuring a consistent and safe user experience throughout the entire network.

The rest and recreation areas along the trails were equipped with wooden gazebos, picnic tables, and trail benches. The placement of the wooden gazebos and picnic tables was carefully chosen in open spaces, offering scenic viewpoints and natural clearings, providing visitors with the opportunity to rest and enjoy the surrounding landscape. These locations were selected not only for their aesthetic appeal but also for their suitability as natural gathering points along the trail network.

The placement of trail benches was determined based on the estimated traversal time and distance between key points of interest. This ensured that hikers would have regular opportunities to rest, particularly in areas where the terrain might be more challenging. By distributing the benches at appropriate intervals, the trail system caters to a diverse range of users, enhancing comfort and accessibility while encouraging longer stays in the area. The overall design of these facilities aimed to harmonize with the natural environment, using sustainable materials and maintaining the ecological balance of the landscape.

2.3.3. Trail Path Ranking—VIKOR Method

Trail ranking is essential for evaluating and optimizing the attractiveness and accessibility of trails, ensuring they meet the needs and preferences of diverse visitor categories. In the present study, the ranking was based on the degree to which the designed trails appeal to all types of visitors, considering various factors such as scenic beauty and difficulty levels. By adopting a comprehensive approach, this method aims to create an inclusive and satisfying experience for different user groups, including families, hikers, and nature enthusiasts, thus enhancing the overall visitor experience and promoting sustainable tourism.

For this purpose, the multi-criteria decision-making (MCDM) process was applied, specifically using the VIKOR method [45]. The VIKOR method was developed to address MCDM problems that involve conflicting and non-commensurable criteria (i.e., criteria measured in different units), assuming that compromise is an acceptable means of resolving conflict. It is particularly suited to situations where the decision-maker seeks a solution as close as possible to the ideal, while alternatives are evaluated across all established criteria. This approach emphasizes the ranking and selection of alternatives in the presence of conflicting objectives, ultimately proposing one or more compromise solutions that reflect a balance between the criteria [46,47]. In this context, VIKOR supports effective decision-making by identifying the best alternatives, based on their proximity to an ideal solution, thus ensuring that diverse and sometimes competing factors are appropriately considered.

For the ranking process, seven criteria were utilized to evaluate the trails: the length of the trail, the hiking time required to complete it, the maximum distance between rest areas found along each trail, the difficulty level, the percentage of the route that consists

of a natural trail rather than a forest road, the average uphill slope, and the extent of the scenic views that visitors can enjoy along the route. These criteria were selected to provide a comprehensive assessment of each trail's quality and appeal, considering both physical and experiential factors that contribute to the overall attractiveness of the trail to different categories of visitors. By integrating these diverse criteria, this study aims to ensure a balanced and thorough evaluation that addresses the practical needs and preferences of hikers and outdoor enthusiasts.

The calculation of hiking time in this study was based on a modified version of Naismith's rule [48,49]. Naismith, in the 19th century, proposed a general guideline for estimating walking times, suggesting that hikers should allocate 20 min for every 1.6 km and an additional 30 min for every 300 m of elevation gain. Over time, more refined rules have been introduced, such as those by Hayes (1994) [50], which provide further detail:

- For flat or uphill terrain, allow 10 min per 1.6 km, plus 10 min for every 300 m of ascent.
- On gentle downhill slopes (less than 150 m per kilometer), allocate 8 min per 1.6 km.
- For steep downhill sections (greater than 150 m per kilometer), allow 10 min per 1.6 km, plus 2 min for every 300 m of descent.
- On rough ground, whether flat, uphill, or gently downhill, allow 15 min per 1.6 km, plus 15 min for every 300 m of descent.
- For rough and steep downhill terrain, allocate 10 min per 1.6 km, plus 10 min for every 300 m of descent.

These guidelines aim to provide a more accurate estimation of hiking time, taking into account variations in terrain and elevation, ensuring a more realistic prediction for different trail conditions.

The viewshed area coverage was determined using the viewshed analysis tool in ArcGIS Desktop version 10.8 software, in combination with a Digital Elevation Model (DEM). This method allowed for precise calculation of the areas visible from different points along the trails, accounting for variations in terrain elevation. By integrating these tools, the analysis provided an accurate representation of the scenic views accessible to hikers throughout the route.

The execution of the VIKOR method first requires the transformation of criteria into a point scale system. In this study, the difficulty level was classified as follows: Difficulty Level 1 = Very Easy, 2 = Easy, 3 = Medium, 4 = Hard, and 5 = Very Hard. Following this, the distinction between beneficial and non-beneficial criteria was made. Beneficial criteria are those where a higher value is preferred, while non-beneficial criteria are those where a lower value is desired (Table 1).

Table 1. Criteria determination for the implementation of the VIKOR method.

Criterion		Units	Weighting Factor	Contribution	Goal
C1	Length	m	0.10	Non beneficial	Minimize
C2	Hiking Time	min	0.05	Non beneficial	Minimize
C3	Maximum Distance between rest areas	m	0.15	Non beneficial	Minimize
C4	Difficulty level	point scale	0.30	Non beneficial	Minimize
C5	Trail Path percentage	percentage	0.05	Beneficial	Maximize
C6	Average Uphill Slope	percentage	0.05	Non beneficial	Minimize
C7	View area coverage	ha *	0.30	Beneficial	Maximize

* 1 ha = 10,000 m^2.

After determining the type of each criterion, a weighting factor scale was established. A structured approach was adopted that integrated both quantitative and qualitative inputs from stakeholders. Initially, stakeholders, including local community representatives, environmental groups, and tourism officials, were engaged through a series of workshops

and surveys to prioritize the factors they deemed most important for trail development. Each participant was asked to rank criteria such as trail length, scenic view coverage, and accessibility based on their perceived importance for enhancing user experience and environmental sustainability. This input was quantitatively analyzed, with each criterion's weight reflecting the frequency and intensity of stakeholder preferences. For instance, scenic view coverage and accessibility to rest areas emerged as high priorities, leading to higher weights for these criteria.

To validate these weights, a consensus-building session was conducted, allowing stakeholders to review the preliminary weighting outcomes and discuss any adjustments needed to align the final weights with collective goals. This iterative process ensured that the final weights used in the VIKOR calculations were both representative of stakeholder input and systematically verified, enhancing the robustness of the trail ranking outcomes. The integration of stakeholder-driven weights allowed the trail design to meet community expectations effectively, balancing ecological considerations with user accessibility.

Based on the analysis of these responses, the final weighting factors were determined and are presented in Table 1. This process ensured that the ranking accurately reflected the preferences and priorities of the stakeholders, providing a solid foundation for the VIKOR-based evaluation of the trails.

After creating the initial matrix with the values of each criterion for every trail (alternative), the application of the VIKOR method follows a structured process consisting of four steps.

The first step involves identifying the best fj^+ and worst fj^- values for each criterion. For beneficial criteria c_j, j = 1, 2, . . ., n, where higher values are preferable, the maximum values are considered as the best, and the minimum values as the worst. The following Equations (1) and (2) are then applied to compute these values accordingly.

If the criterion j is beneficial, maximum values are best and minimum values worst minimum, and Equation (1) is applied.

$$f_j^+ = max\left(f_{ij}\right), f_j^- = min\left(f_{ij}\right) \tag{1}$$

If it is non beneficial, minimum values are best and maximum values are worst and Equation (2) are applied.

$$f_j^+ = min\left(f_{ij}\right), f_j^- = max\left(f_{ij}\right) \tag{2}$$

The second step consists of the calculation of unity measure S_i for each alternative.

$$S_i = \sum_{j=1}^{m} \left(W_j \ * \ \frac{X_i^+ - X_{ij}}{X_i^+ - X_i^-} \right) \tag{3}$$

where S_i: the unity measure, W_j: the weighting factor of each criterion, X_i^+ and X_i^-: best and the worst value of each criterion, X_{ij}: the value of the criterion of each alternative.

The third step consists of the calculation of individual regret R_i for each alternative.

$$R_i = max\left(W_j * \frac{X_i^+ - X_{ij}}{X_i^+ - X_i^-} \right) \tag{4}$$

After the calculation of S_i and R_i for each alternative, the best and the worst values are calculated as follows:

$$S^+ = min(S_i), \ S^- = max(S_i), \ R^+ = min(R_i), \ R^- = max(R_i) \tag{5}$$

The fourth step consists of the calculation of the value Q_i.

$$Q_i = v \ * \ \frac{S_i - \ S^+}{S^- - S^+} + (1 - v) \ * \ \frac{R_i - R^+}{R^- - R^+} \tag{6}$$

The parameter v represents the weight for the strategy of maximizing group utility, and it can take values between 0 and 1. As noted by San Cristóbal (2011), the calculation of the Q_i value was performed for different values of the parameter v. In the present application, to optimize the results, the value of v was set to 0.5, balancing the emphasis between individual regret minimization and group utility maximization. This choice ensures a more balanced compromise solution, taking into account both perspectives.

After the calculation, the alternatives are ranked based on the minimum Q_i value, and in addition ranking based on S_i and R_i. The decision maker can select the best alternative based on Q_i value ranking. The results are three ranking lists. The alternative A^1 to the best ranked by the measure Q (minimum) is proposed as a compromise solution if two condition are satisfied:

- Condition 1: acceptable advantage

$$Q\left(A^2\right) - Q\left(A^1\right) \geq DQ \tag{7}$$

  where $DQ = \frac{1}{j-1}$ with j as the number of alternatives, A^1: the first best alternative based on Qi(min) value ranking, A^2: the second-best alternative based on Qi(min)
- Condition 2: Acceptable stability in decision making. Alternative A^1 must also be ranked by S or/and R as best.

If Condition 1 is not met, a set of compromise solutions is suggested, which includes $\left\{A^1, A^2\right\}$. If Condition 2 is not met, a set of compromise solutions is proposed, consisting of $\left\{A^1, A^2, ..., A^m\right\}$, where A^m is determined by Equation (8):

$$Q(A^m) - Q\left(A^1\right) < DQ \tag{8}$$

The compromise solution includes those alternatives that are ranked among the top M positions in the Q list. The selection of these alternatives is based on their relative "closeness", meaning the difference between their Q values and that of the best alternative is less than a specified threshold, DQ. This ensures that all alternatives within a certain proximity to the optimal solution are considered as part of the compromise set.

3. Results

3.1. Geospatial Data and POI

The total length of the forest road network in the study area amounts to 107.22 km. In certain sections of the proposed trails, the forest roads were utilized as part of the trail routes, where this integration was deemed appropriate for both accessibility and preservation of the natural landscape. These sections allow for the efficient use of existing infrastructure while maintaining the integrity of the surrounding environment.

As illustrated in the Figure 3, a total of 38 points of interest (POIs) were identified through a collaborative process involving all relevant stakeholders. These POIs, which are critical to both the ecological and cultural significance of the area, were marked and described in detail, offering visitors a well-rounded experience of the region's natural and historical assets. The POIs are shown in the map and described in Table 2.

This comprehensive identification of points of interest not only enhances the visitor experience by showcasing both cultural and natural highlights but also helps in the conservation and promotion of these areas. The integration of forest roads and the design of the trail network ensure that visitors can access these points while preserving the ecological and scenic values of the region. The detailed topographic, slope, and elevation models included in Figure 3 further contribute to the understanding of the area's terrain, aiding in both the planning and implementation of sustainable trail development.

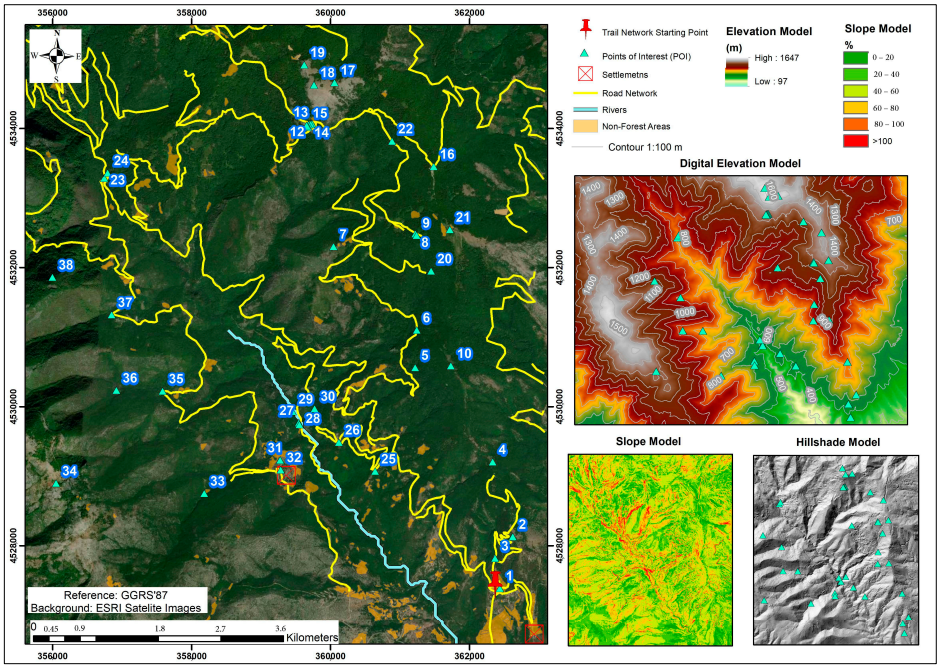


Figure 3. Geospatial data of the research area analyzed for the design of the trail paths.

Table 2. Points of interest within the research area.

ID	Name/Description	ID	Name/Description
1	Church of St. Paraskevi	20	Stone Bridge
2	Viewing Area—Wooden Structure	21	Open area of Germanos
3	Roman Path	22	Petridis Fountain
4	Open area of Aloni	23	Fasianos Shelter
5	Wild Hazelnut Trees	24	Virout Springs
6	Tasos' Natural Spring	25	Water Trough—Fountain
7	Varnitsa Shelter	26	Exaerosi, Viewing Point
8	Bela Voda Natural Spring	27	Stone Bridge
9	Bela Voda Lake	28	Gramoska Stream
10	Viewing Area—Geodetic Base of Hellenic Military Geographical Service	29	Rock Pools
11	Ottoman Fountain	30	Natural Spring
12	Old Hiking Shelter BAO	31	Kromni Primary School
13	New Hiking Shelter BAO	32	Church of St. Nicholas
14	Viewing Area	33	Freatia Location, Kromni Springs
15	Cross, viewing area, resting spot	34	Area of Tservena Bara
16	Kastaneri Junction, resting spot	35	Delta Water Trough
17	Stone Kiosk, resting spot	36	Delta Point, Wildlife Refuge
18	PAIKO Peak	37	Water Troughs, Natural Springs
19	Gola Tsouka Peak	38	Kromni Park

3.2. Designed Trail Paths

A total of 19 trail paths were designed, covering a cumulative distance of 81.77 km. These routes include 14 recreational trails, 1 thematic trail, and 4 cycling routes.

Each of these trail paths was assigned a unique identification code (ID) according to the specifications of the Greek naming system. For all the trail paths, the ID begins with the letter 'T', indicating that they are part of the national trail network. This is followed by

a three-letter code representing the Regional Unit. Since all the routes are located within the Municipality of Pellas in the Regional District of Pella, the letters "PEL" are included in the reference code to signify this geographical region. After the regional identifier, the next character in the code specifies the type of trail. "E" is used for recreational trails, "L" for the thematic trail, and "B" for the cycling routes. Following this, the number "16" is added, signifying that this is the 16th trail network established in the area. Lastly, a sequential number is assigned to distinguish each specific route within the network. This systematic approach to trail coding ensures clarity and ease of reference for both users and administrators, allowing for efficient management and promotion of the trail system within the national and regional contexts.

Table 3 provides an overview of the key characteristics of the designed trail paths. Additionally, Figure 4 illustrates the final placement of these paths along with the outcomes of the trail facility allocation.

Table 3. Attributes of designed trail paths.

ID	Name	Type	Length (m)	Difficulty Level	Trail Characterization	
					Path (%)	Ground Road (%)
T-PEL E 16.1	Agia Paraskevi—Bela Voda	Recreational	6662	Very Easy	93	7
T-PEL E 16.2	Agia Paraskevi—Gola Tsouka	Recreational	8098	Medium	69	31
T-PEL L 16.3	Mystery Trail—Varnitsa Shelter	Thematic	4097	Easy	93	7
T-PEL E 16.4	BAO Giannitsa Shelter	Recreational	14,297	Easy	0	100
T-PEL E 16.5	Bela Voda—Roman Path	Recreational	702	Medium	100	0
T-PEL E 16.6	Bela Voda	Recreational	836	Hard	100	0
T-PEL E 16.7	Kromni	Recreational	1887	Medium	100	0
T-PEL E 16.8	Varnitsa Shelter—BAO Shelter	Recreational	4569	Medium	74	26
T-PEL E 16.9	Exaerosi—Tasos Natural Spring	Recreational	2141	Medium	82	18
T-PEL E 16.10	Vathres (Rock Pools)	Recreational	193	Medium	100	0
T-PEL E 16.11	Fasianos Shelter—BAO Shelter	Recreational	4394	Medium	95	5
T-PEL E 16.12	Kromni—Tservena Bara	Recreational	4576	Medium	100	0
T-PEL E 16.13	Delta Water	Recreational	1216	Medium	100	0
T-PEL E 16.14	Kromni—Water Troughs, Natural Springs	Recreational	4977	Medium	100	0
T-PEL E 16.15	Remma	Recreational	1037	Medium	100	0
T-PEL B 16.16	Over Time	Cycling	1340	Very Hard	100	0
T-PEL B 16.17	Break	Cycling	702	Hard	100	0
T-PEL B 16.18	Forest Road—Fasianos Shelter	Cycling	9615	Medium	36	64
T-PEL B 16.19	Kromni—Fasianos	Cycling	10,424	Easy	0	100

One of the routes was classified as very easy, three as easy, twelve as medium difficulty, two as hard, and one as very hard. Of the total length of the trails, 56.03% (equivalent to 45.82 km) involves the creation of new pathways, while the remaining 43.97% (equivalent to 35.95 km) runs parallel to the existing forest road network.

For the sections where new trails will be created, only 1.23 km will require Level 2 vegetation clearance, which involves more intensive clearing due to denser vegetation. In the remaining sections, a less intensive Level 1 clearance will be sufficient. This classification and management of trail difficulty and required maintenance ensures a sustainable balance between providing accessible routes for different user groups and preserving the natural environment. The integration of both newly created paths and the utilization of existing forest roads demonstrates an efficient approach to trail development that maximizes resource use while minimizing environmental impact. Table 4 provides an overview of the key geometric features of the designed paths, which include elevation and slope technical features.

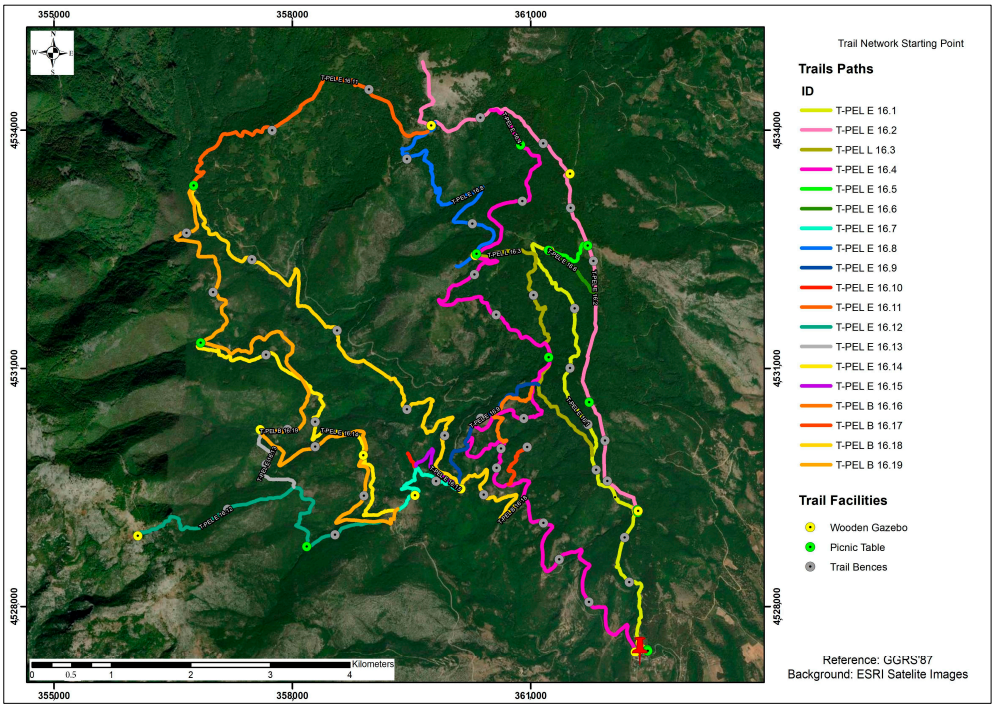


Figure 4. Map of the designed trail path network and the trail facilities.

Table 4. Geometric and technical feature of the designed trail paths.

ID	Minimum Elevation (m)	Mean Elevation (m)	Maximum Elevation (m)	Maximum Uphill Slope (%)	Maximum Downhill Slope (%)	Average Uphill Slope (%)	Average Downhill Slope (%)
T-PEL E 16.1	484	920	1261	32.5	62.2	9.8	16.2
T-PEL E 16.2	823	1264	1606	30.5	21.9	7.8	16.4
T-PEL L 16.3	884	1016	1212	60.7	61.1	14	18.3
T-PEL E 16.4	485	832	1324	23.5	33.3	5.5	9.2
T-PEL E 16.5	1265	1306	1363	67.1	30.9	17.0	9.8
T-PEL E 16.6	1256	1265	1279	40.2	80.1	9.9	11.6
T-PEL E 16.7	450	495	569	41.2	44.9	16.1	16.4
T-PEL E 16.8	988	1132	1348	25.9	41.9	8.8	16.3
T-PEL E 16.9	544	695	893	11.2	49.8	3.7	17.2
T-PEL E 16.10	435	460	464	17.6	33.3	3.7	10.9
T-PEL E 16.11	809	1171	1330	56.8	56.2	11.0	19.4
T-PEL E 16.12	604	890	1307	39.1	47.5	8.6	18.3
T-PEL E 16.13	768	793	840	46.4	42.2	15.3	13.3
T-PEL E 16.14	560	735	908	37.0	40.4	11.4	13.9
T-PEL E 16.15	455	510	546	26.9	34.5	9.4	12.8
T-PEL B 16.16	629	735	857	33.9	23.6	19.7	9.1
T-PEL B 16.17	598	667	746	44.7	21.4	22.7	6.2
T-PEL B 16.18	537	638	809	27.3	34.3	9.2	10.3
T-PEL B 16.19	569	766	903	28.3	31.0	8.4	9.3

Figure A1 provide a tangible sense of the habitat conditions and landscape diversity surrounding the trail network. This figure presents selected views from key sections of the network, highlighting characteristic terrain, vegetation, and natural features that define the area.

3.3. Trail Facilities and Signage

The proposed signage system includes the installation of 12 main signs, 113 information signs, and 380 direction signs, providing clear and relevant information for hikers, cyclists, and other users. The main signs are placed at key locations and junctions, with double-sided panels and small shelters for protection. The left panel displays general information about the trail network, including a map of the Paiko area, showing the entire trail system and key landmarks. The right panel provides specific details about the current trail segment, such as points of interest and conditions. A map shows the user's current location and the path to the next segment. Additionally, these signs include trail regulations, safety information, and alternative routes or detours.

The information signs are placed along the trails and display the remaining distance in hours and kilometers, in both Greek and English. They also mark important locations such as viewpoints, rest areas, and potential hazard zones to help users track progress and stay safe. The 380 direction signs guide users throughout the network. Each sign uses color codes and symbols that correspond to specific trails, ensuring easy identification. They also feature the trail number and, for cycling routes, a bicycle symbol. Additionally, the signs display trail rules such as prohibitions on hunting, lighting fires, and proper waste disposal to protect the environment.

The signage system is designed for visibility and durability, ensuring it remains functional and easy to spot in various weather conditions. This system enhances safety, navigation, and enjoyment for all users. The overall locations and types of signs are presented in Figure 5. In addition, Figure 5 contains the classification of the designed trails regarding the characterization, the path type and the difficulty level.

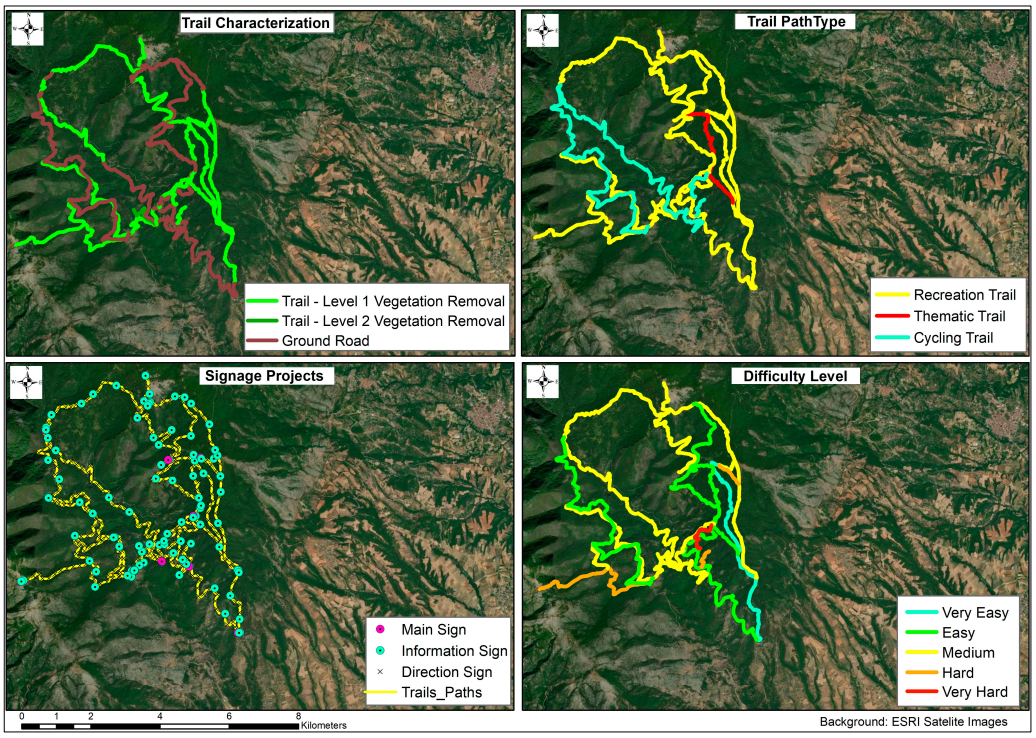


Figure 5. Overview of trail system showing vegetation removal, trail types, signage locations, and difficulty levels on satellite imagery.

The designed trail network will feature 44 benches, 12 wooden gazebos, and 13 picnic tables to enhance user comfort and convenience. The benches will be strategically placed along the trails, providing spots for rest and scenic views. The wooden gazebos will offer shelter at key locations, allowing visitors to pause and enjoy the surroundings in comfort, even during adverse weather conditions. Additionally, the picnic tables will be located at

designated areas, encouraging visitors to take breaks and enjoy meals in the natural setting of the trail network. This infrastructure enhances both the functionality and enjoyment of the trails.

3.4. Trail Ranking

For the application of the VIKOR method in ranking the designed trail paths, the initial matrix was created, as shown in Table 5, displaying the values for all criteria. Additionally, Figure A2 presents the viewshed analysis for the designated trail paths, specifically illustrating the areas visible from various points along each trail. This analysis is crucial in evaluating the 'view area coverage' criterion used within the VIKOR method, as it quantifies the scenic visibility accessible to trail users. The color-coded map in Figure A2 reflects the visible zones for each trail path. This visualization supports an understanding of how each trail performs in offering expansive views, which are integral to enhancing user experience and aligning with this study's environmental and recreational goals. By comparing visibility across trails, Figure A2 provides insights into each path's capacity to meet the visual exposure criterion, directly influencing the ranking outcomes.

Table 5. Initial matrix for the ranking of the trail paths by the VIKOR method.

Trail Path	Ranking criteria						
	C1	C2	C3	C4	C5	C6	C7
	Length (m)	Hiking Time (min) *	Maximum Distance Between Rest Areas (m)	Difficulty Level	Trail Path (%)	Average Uphill Slope (%)	View Area Coverage (ha)
T-PEL E 16.1	6662	71	1334	1	93	9.8	3101.5
T-PEL E 16.2	8098	89	1820	3	69	7.8	3992.1
T-PEL L 16.3	4097	33	1626	2	93	14	2773.6
T-PEL E 16.4	14,297	183	2071	2	0	5.5	3441.7
T-PEL E 16.5	702	24	702	3	100	17.0	2047.1
T-PEL E 16.6	836	11	836	4	100	9.9	2174.0
T-PEL E 16.7	1887	46	1182	3	100	16.1	1342.9
T-PEL E 16.8	4569	62	2655	3	74	8.8	2411.4
T-PEL E 16.9	2141	12	1172	3	82	3.7	2117.5
T-PEL E 16.10	193	2	193	3	100	3.7	44.8
T-PEL E 16.11	4394	48	1695	3	95	11.0	2480.3
T-PEL E 16.12	4576	45	2090	3	100	8.6	2559.4
T-PEL E 16.13	1216	22	668	3	100	15.3	1532.5
T-PEL E 16.14	4977	69	1387	3	100	11.4	2746.7
T-PEL E 16.15	1037	22	1037	3	100	9.4	930.2
T-PEL B 16.16	1340	39 *	1340	5	100	19.7	1771.3
T-PEL B 16.17	702	22 *	702	4	100	22.7	1598.8
T-PEL B 16.18	9615	145 *	1981	3	36	9.2	2527.3
T-PEL B 16.19	10,424	176 *	2858	2	0	8.4	3132.1

* The traversal time for the cycling routes was calculated by treating them as pedestrian paths.

In terms of trail length, the best value among the trail paths (alternatives) is 193 m, while the worst value is 14,297 m. For hiking time, the optimal value is 2 min, and the longest is 183 min. Regarding the maximum distance between rest areas, the best value is 193 m, and the worst is 2858 m. For the difficulty level, the best value is 1 (Very Easy), and the worst is 5 (Very Hard). Concerning the trail composition, the best value is 100% trail path, while the worst is 0%, indicating a forest road. The average uphill slope ranges

from 3.7% (best) to 22.7% (worst). Finally, for the view area coverage, the best value is 3992.1 hectares, and the worst is 44.8 hectares.

The implementation of the VIKOR method produced the results shown in Table A1. The final outcomes, after applying the method, are presented in Table 6. These results reflect the ranking of the trail paths based on the multiple criteria used, including factors such as length, difficulty level, and view area coverage. The VIKOR method helped identify the best compromise solutions among the alternatives, ensuring an optimal balance between the diverse needs and preferences of trail users.

Table 6. Final ranking of the designed trail paths after the implementation of the VIKOR method.

ID	Name	Rank
T-PEL E 16.1	Agia Paraskevi—Bela Voda	1
T-PEL L 16.3	Mystery Trail—Varnitsa Shelter	2
T-PEL E 16.2	Agia Paraskevi—Gola Tsouka	3
T-PEL E 16.4	BAO Giannitsa Shelter	4
T-PEL E 16.5	Bela Voda—Roman Path	5
T-PEL E 16.9	Exaerosi—Tasos Natural Spring	6
T-PEL E 16.14	Kromni—Water Troughs, Natural Springs	7
T-PEL E 16.11	Fasianos Shelter—BAO Shelter	8
T-PEL E 16.12	Kromni—Tservena Bara	9
T-PEL E 16.13	Delta Water	10
T-PEL B 16.19	Kromni—Fasianos	11
T-PEL E 16.8	Varnitsa Shelter—BAO Shelter	12
T-PEL B 16.18	Forest Road—Fasianos Shelter	13
T-PEL E 16.6	Bela Voda	14
T-PEL E 16.7	Kromni	15
T-PEL E 16.15	Remma	16
T-PEL B 16.17	Break	17
T-PEL E 16.10	Vathres (Rock Pools)	18
T-PEL B 16.16	Over Time	19

4. Discussion

The trail network designed for the Mount Paiko region successfully balances the needs of tourists, local communities, and environmental preservation. With a total of 19 trail paths, including 14 recreational trails, 1 thematic trail, and 4 cycling routes, this study covers a variety of difficulty levels and user experiences, catering to a diverse range of visitors—from casual hikers to experienced adventurers. The inclusion of essential infrastructure such as signage, rest areas, and accessible trails for individuals reflects an emphasis on inclusivity and safety. The use of the VIKOR method to rank the trails provides a structured approach to decision-making, accounting for conflicting criteria such as trail length, difficulty, scenic value, and infrastructure availability. The top-ranked trail (T-PEL E 16.1, Agia Paraskevi—Bela Voda) highlights how the integration of scenic beauty, ease of access, and user-friendly facilities can enhance a trail's attractiveness to a broad audience.

The development of semi-mountainous and mountainous areas, as seen in this project, plays a crucial role in promoting both sustainable tourism and regional development. Similar to previous studies on trail-based tourism [51,52], this research emphasizes the dual benefits of economic stimulation for local communities and the conservation of natural resources. The trail network not only facilitates outdoor recreation but also promotes

environmental awareness by showcasing the region's natural and cultural assets. One of the standout aspects of this study is the emphasis on inclusive design. Trails were created with varying levels of difficulty to accommodate all user groups, including families, older adults, and individuals with physical limitations. By providing easy-to-navigate paths, accessible rest areas, and well-distributed signage, the project ensures that nature-based tourism is open to everyone, aligning with the principles of equitable access to outdoor spaces [53].

The strategic allocation of trail facilities, including benches, gazebos, picnic tables, and clear signage, enhances both the safety and enjoyment of the trails. The importance of rest areas and directional signage cannot be overstated in ensuring a positive user experience [54]. Well-placed facilities contribute to user comfort, reduce fatigue, and encourage longer stays in the area, all of which increase the economic benefits for local businesses. Additionally, the clear signage system promotes responsible use of the environment by guiding visitors and informing them of the ecological importance of the area.

The development of these trail networks demonstrates how semi-mountainous and mountainous areas can be transformed into sustainable tourism hubs. By designing trails that minimize environmental impact while maximizing tourist engagement, this study supports the long-term ecological sustainability of the region [55]. Moreover, the inclusion of cycling routes, thematic trails, and educational opportunities ensures that the region offers diverse tourism experiences [56]. This variety not only appeals to different segments of the tourist population but also helps distribute visitor impact more evenly across the landscape, reducing the risk of environmental degradation in sensitive areas.

The trail paths developed in Mount Paiko are designed to enrich environmental awareness while promoting biodiversity conservation. Unlike traditional roads or tourist facilities, these trail paths have a minimal footprint, strategically routed to avoid sensitive habitats, and reduce environmental disturbance [57,58]. By guiding visitors along designated paths, the trails help to concentrate human activity in specific areas, thus limiting broader impacts on the surrounding ecosystem. This approach not only minimizes habitat fragmentation but also fosters a deeper appreciation for the local biodiversity, as visitors experience the natural environment in a low-impact, immersive way [59,60]. The trails serve as educational conduits, encouraging sustainable interaction with nature and promoting conservation values among visitors, thereby supporting the long-term ecological integrity of Mount Paiko.

An important aspect of this study is its cost-effectiveness compared to other approaches in promoting ecotourism and sustainable economic development. Unlike large-scale infrastructure projects or high-investment tourist facilities, the design and implementation of trail networks in semi-mountainous areas, as proposed here, require relatively modest financial resources [61,62]. By focusing on the development of natural trails with minimal environmental impact, this approach supports sustainable tourism. Additionally, using multi-criteria decision-making tools, such as the VIKOR method, allows for the optimal allocation of resources by prioritizing trails that best balance ecological conservation and visitor accessibility. This method not only enhances the value derived from limited budgets but also serves as a replicable, low-cost model for similar regions aiming to promote ecotourism sustainably.

The VIKOR method's implementation in this context provided a clear, objective framework for evaluating the trails. By considering both beneficial (e.g., scenic views) and non-beneficial criteria (e.g., difficulty level and distance between rest areas), the VIKOR approach allowed the research team to rank trails based on a compromise solution that best serves the overall goals of sustainability and user satisfaction. The multi-criteria nature of the method is particularly useful in contexts like trail design, where conflicting priorities—such as environmental protection and tourist accessibility—must be balanced. This study builds on prior work [63], by demonstrating how the VIKOR method can be adapted for tourism planning and infrastructure development in natural areas. The ranking

of trails based on a range of factors ensures that resources can be allocated effectively, focusing on the most promising trails that meet user needs and environmental standards.

While the VIKOR method was chosen for this study due to its strength in handling conflicting criteria and providing compromise solutions, it is valuable to consider how it compares to other decision-making approaches, such as the Analytic Hierarchy Process (AHP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [64]. AHP is widely used for its hierarchical structuring of decision criteria and pairwise comparison capabilities, making it effective in scenarios where criteria weights are based on expert judgment. However, it may lack the same robustness as VIKOR in resolving conflicts between criteria. TOPSIS, on the other hand, ranks alternatives by their distance from an ideal solution, similar to VIKOR, but does not emphasize a compromise solution that VIKOR uniquely provides. Thus, while AHP and TOPSIS offer valuable insights, particularly in weight determination and ranking efficiency [65], VIKOR's approach of balancing conflicting criteria makes it especially suitable for this study's goal of optimizing trail paths in a way that respects both ecological and accessibility considerations.

While this study offers significant contributions to trail planning and regional development, certain limitations should be acknowledged. The reliance on stakeholder input for weighting the VIKOR criteria could introduce subjective biases, particularly in the evaluation of non-quantifiable factors such as scenic value. Future research could incorporate real-time visitor data, such as satisfaction surveys or GPS tracking, to provide a more dynamic assessment of trail usage patterns. Furthermore, the long-term impact of increased tourist activity on the natural environment requires ongoing monitoring. Studies that track the ecological effects of tourism, such as wildlife disturbance or soil erosion, will be critical in ensuring the sustainability of the trail network. Additionally, expanding this methodology to other semi-mountainous areas, both in Greece and internationally, could validate the effectiveness of the VIKOR method in different environmental and cultural contexts.

5. Conclusions

In conclusion, this study provides a comprehensive framework for designing and optimizing trail networks in semi-mountainous and mountainous areas, emphasizing both environmental sustainability and user inclusivity. By employing the MCDM-VIKOR method, the research effectively ranked trails based on multiple criteria, ensuring that the most accessible and environmentally suitable paths were prioritized. This approach not only caters to diverse visitor preferences, from casual hikers to experienced adventurers but also strengthens the conservation efforts necessary for protecting fragile ecosystems. The successful integration of stakeholder perspectives further reinforces the value of participatory planning in fostering community engagement and ensuring that the trail networks serve both local populations and tourists alike.

Moreover, the findings of this research hold significant implications for the sustainable development of rural areas beyond Greece. The replicable methodology, particularly the use of the VIKOR method in evaluating and ranking trails, can be applied to similar projects in other regions facing the challenge of balancing tourism development with environmental preservation.

This study's findings highlight the successful application of the MCDM-VIKOR method in designing a sustainable and inclusive trail network within Mount Paiko's semi-mountainous and mountainous areas. By evaluating 19 trails based on multiple criteria—such as trail length, difficulty, scenic value, and accessibility—the framework prioritized trails that balanced visitor needs and ecological preservation. The top-ranked trails, like Agia Paraskevi—Bela Voda, integrated scenic beauty with accessible infrastructure, enhancing both user satisfaction and environmental stewardship. The results show that this structured approach can effectively support regional economic development through ecotourism while preserving biodiversity. This framework also demonstrates replicability for similar regions, offering a model for sustainable tourism and economic growth rooted in environmental conservation.

As the demand for outdoor recreational activities continues to rise, particularly in the post-pandemic era, well-planned and inclusive trail systems present a viable path toward promoting public health, enhancing local economies, and preserving natural landscapes. Future research could build on this foundation by incorporating real-time visitor data to further refine trail rankings and monitor the long-term ecological impacts of increased tourism.

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Appendix A

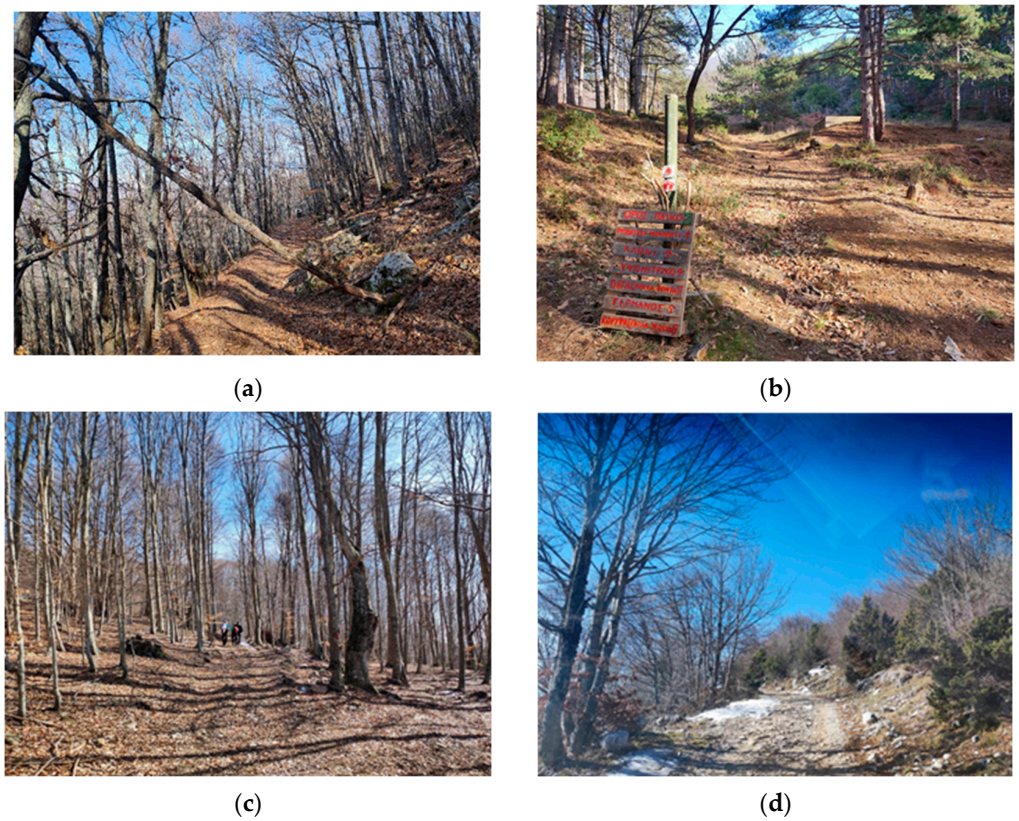


Figure A1. (**a**) Section of trail path T-PEL E 16.2 at the midpoint of the route. (**b**) The starting point of trail path T-PEL E 16.2. (**c**) The trail path of route T-PEL E 16.4. (**d**) Forest road (ground road) along a section of route T-PEL E 16.9.

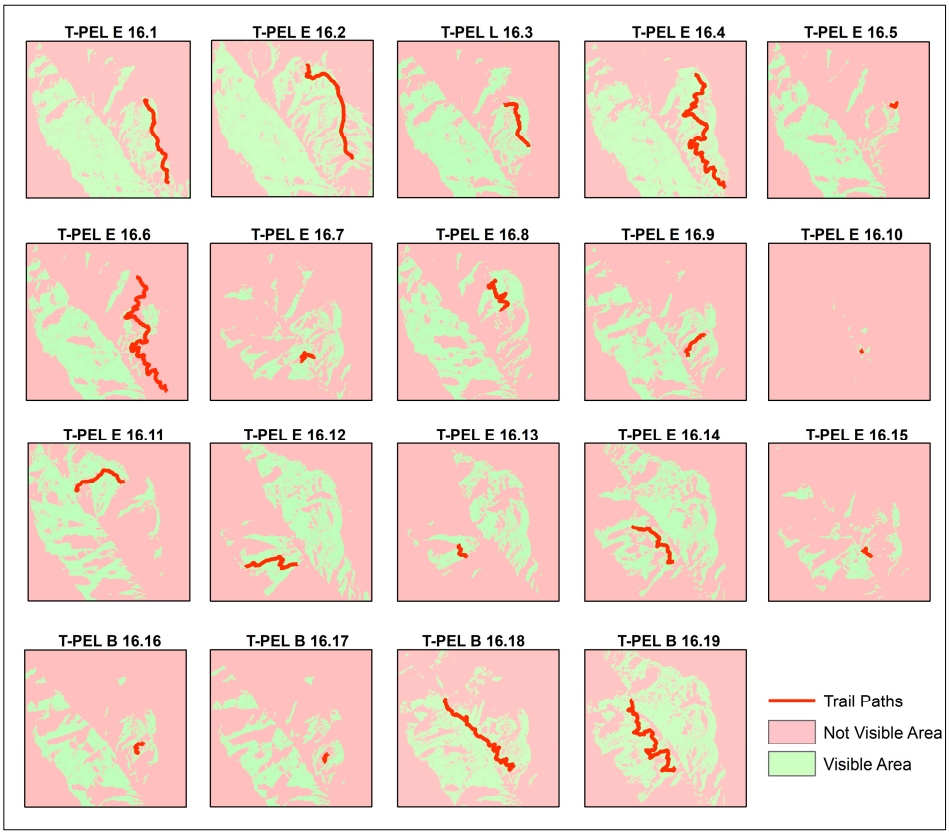


Figure A2. Viewshed analysis of the designed paths for the calculation of the view area coverage criterion of the VIKOR method.

Table A1. Values of implementing the VIKOR method for the ranking of the designed trail paths.

Trail Path	Si							$\sum Si$	Ri	Qi
	C1	C2	C3	C4	C5	C6	C7			
T-PEL E 16.1	0.04587	0.01906	0.06422	0.00000	0.00350	0.01605	0.06768	0.21639	0.06768	0.00000
T-PEL E 16.2	0.05605	0.02403	0.09158	0.15000	0.01550	0.01079	0.00000	0.34795	0.15000	0.35145
T-PEL L 16.3	0.02768	0.00856	0.08066	0.07500	0.00350	0.02711	0.09261	0.31511	0.09261	0.18443
T-PEL E 16.4	0.10000	0.05000	0.10570	0.07500	0.05000	0.00474	0.04183	0.42727	0.10570	0.36120
T-PEL E 16.5	0.00361	0.00608	0.02865	0.15000	0.00000	0.03500	0.14782	0.37116	0.15000	0.38221
T-PEL E 16.6	0.00456	0.00249	0.03619	0.22500	0.00000	0.01632	0.13818	0.42273	0.22500	0.61195
T-PEL E 16.7	0.01201	0.01215	0.05567	0.15000	0.00000	0.03263	0.20134	0.46381	0.20134	0.61545
T-PEL E 16.8	0.03103	0.01657	0.13857	0.15000	0.01300	0.01342	0.12013	0.48273	0.15000	0.53002
T-PEL E 16.9	0.01381	0.00276	0.05510	0.15000	0.00900	0.00000	0.14247	0.37315	0.15000	0.38484
T-PEL E 16.10	0.00000	0.00000	0.00000	0.15000	0.00000	0.00000	0.30000	0.45000	0.30000	0.80949
T-PEL E 16.11	0.02979	0.01271	0.08454	0.15000	0.00250	0.01921	0.11490	0.41364	0.15000	0.43849
T-PEL E 16.12	0.03108	0.01188	0.10677	0.15000	0.00000	0.01289	0.10889	0.42151	0.15000	0.44891
T-PEL E 16.13	0.00725	0.00552	0.02674	0.15000	0.00000	0.03053	0.18694	0.40698	0.18694	0.50915
T-PEL E 16.14	0.03392	0.01851	0.06720	0.15000	0.00000	0.02026	0.09465	0.38455	0.15000	0.39994
T-PEL E 16.15	0.00598	0.00552	0.04750	0.15000	0.00000	0.01500	0.23271	0.45672	0.23271	0.67356
T-PEL B 16.16	0.00813	0.01022	0.06456	0.30000	0.00000	0.04211	0.16878	0.59380	0.30000	1.00000
T-PEL B 16.17	0.00361	0.00552	0.02865	0.22500	0.00000	0.05000	0.18190	0.49468	0.22500	0.70726
T-PEL B 16.18	0.06680	0.03950	0.10064	0.15000	0.03200	0.01447	0.11133	0.51474	0.15000	0.57243
T-PEL B 16.19	0.07254	0.04807	0.15000	0.07500	0.05000	0.01237	0.06536	0.47333	0.15000	0.51757

References

1. Schneiderbauer, S. Chapter 19—Challenges and opportunities for sustainable development in European mountains (Europe—Introduction). In *Safeguarding Mountain Social-Ecological Systems*; Schneiderbauer, S., Pisa, P.F., Shroder, J.F., Szarzynski, J., Eds.; Elsevier: Amsterdam, The Netherlands, 2024; Volume 2, pp. 153–156. [CrossRef]
2. Peng, J.; Ma, J.; Du, Y.; Zhang, L.; Hu, X. Ecological suitability evaluation for mountainous area development based on conceptual model of landscape structure, function, and dynamics. *Ecol. Indic.* **2016**, *61*, 500–511. [CrossRef]
3. Milićević, S.; Bošković, N.; Lakićević, M. Sustainable tourism development in mountain areas in Šumadija and Western Serbia. *J. Mt. Sci.* **2021**, *18*, 735–748. [CrossRef]
4. Lun, L.-M.; Pechlaner, H.; Volgger, M. Rural Tourism Development in Mountain Regions: Identifying Success Factors, Challenges and Potentials. *J. Qual. Assur. Hosp. Tour.* **2016**, *17*, 389–411. [CrossRef]
5. Tampakis, S.; Andrea, V.; Karanikola, P.; Pailas, I. The Growth of Mountain Tourism in a Traditional Forest Area of Greece. *Forests* **2019**, *10*, 1022. [CrossRef]
6. Tsiotas, D.; Kantartzis, A.; Kolkos, G.; Lemonakis, P.; Arabatzis, G. A multilayer network methodological framework for transportation and development of mountainous areas. *Int. J. Sustain. Agric. Manag. Inform.* **2024**, *10*, 378–404. [CrossRef]
7. Tzanelli, R.; Korstanje, M.E. Tourism in the European economic crisis: Mediatised worldmaking and new tourist imaginaries in Greece. *Tour. Stud.* **2016**, *16*, 296–314. [CrossRef]
8. Gimouki, E. Sustainable Tourism Development in Less Touristy Destinations; The Case of Epirus, Greece. In *Sustainable Tourism, Culture and Heritage Promotion*; Chica-Olmo, J., Vujičić, M., Castanho, R.A., Stankov, U., Martinelli, E., Eds.; Springer Nature: Cham, Switzerland, 2024; pp. 13–20.
9. Spiliopoulou, K.; Dimitrakopoulos, P.G.; Brooks, T.M.; Kelaidi, G.; Paragamian, K.; Kati, V.; Oikonomou, A.; Vavylis, D.; Trigas, P.; Lymberakis, P.; et al. The Natura 2000 network and the ranges of threatened species in Greece. *Biodivers. Conserv.* **2021**, *30*, 945–961. [CrossRef]
10. Papadaki, E. Promoting Green Tourism Synergies with Cultural and Creative Industries: A Case Study of Greece. *Sustainability* **2024**, *16*, 633. [CrossRef]
11. Kasimati, E.; Ioakeimidis, P. Accessible tourism in Greece: What is the current status? *J. Ekon.* **2019**, *1*, 33–42.
12. Schismenos, S.; Zaimes, G.N.; Iakovoglou, V.; Emmanouloudis, D. Environmental sustainability and ecotourism of riparian and deltaic ecosystems: Opportunities for rural Eastern Macedonia and Thrace, Greece. *Int. J. Environ. Stud.* **2019**, *76*, 675–688. [CrossRef]
13. Kyvelou, S.S.; Gourgiotis, A. Landscape as Connecting Link of Nature and Culture: Spatial Planning Policy Implications in Greece. *Urban Sci.* **2019**, *3*, 81. [CrossRef]
14. Rice, W.L.; Mateer, T.J.; Reigner, N.; Newman, P.; Lawhon, B.; Taff, B.D. Changes in recreational behaviors of outdoor enthusiasts during the COVID-19 pandemic: Analysis across urban and rural communities. *J. Urban Ecol.* **2020**, *6*, juaa020. [CrossRef]
15. Hansen, A.S.; Beery, T.; Fredman, P.; Wolf-Watz, D. Outdoor recreation in Sweden during and after the COVID-19 pandemic—Management and policy implications. *J. Environ. Plan. Manag.* **2023**, *66*, 1472–1493. [CrossRef]
16. Beery, T.; Olsson, M.R.; Vitestam, M. COVID-19 and outdoor recreation management: Increased participation, connection to nature, and a look to climate adaptation. *J. Outdoor Recreat. Tour.* **2021**, *36*, 100457. [CrossRef]
17. Coventry, P.A.; Brown, J.V.E.; Pervin, J.; Brabyn, S.; Pateman, R.; Breedvelt, J.; Gilbody, S.; Stancliffe, R.; McEachan, R.; White, P.C.L. Nature-based outdoor activities for mental and physical health: Systematic review and meta-analysis. *SSM-Popul. Health* **2021**, *16*, 100934. [CrossRef]
18. Jackson, S.B.; Stevenson, K.T.; Larson, L.R.; Peterson, M.N.; Seekamp, E. Outdoor Activity Participation Improves Adolescents' Mental Health and Well-Being during the COVID-19 Pandemic. *Int. J. Environ. Res. Public Health* **2021**, *18*, 2506. [CrossRef]
19. Kyriakopoulos, G.L. Land Use Planning and Green Environment Services: The Contribution of Trail Paths to Sustainable Development. *Land* **2023**, *12*, 1041. [CrossRef]
20. Kantartzis, A.; Lemonakis, P.; Malesios, C.; Daoutis, C.; Galatsidas, S.; Arabatzis, G. Attitudes and Views of Citizens Regarding the Contribution of the Trail Paths in Protection and Promotion of Natural Environment. *Land* **2022**, *11*, 1585. [CrossRef]
21. Godtman Kling, K.; Fredman, P.; Wall-Reinius, S. Trails for tourism and outdoor recreation: A systematic literature review. *Tour. Int. Interdiscip. J.* **2017**, *65*, 488–508.
22. Lukoseviciute, G.; Pereira, L.N.; Panagopoulos, T.; Fedeli, G.; Ramsey, E.; Madden, K.; Condell, J. Recreational trail development within different geographical contexts as a determinant of income multiplier and local economic impact. *Tour. Manag. Perspect.* **2023**, *46*, 101090. [CrossRef]
23. Baxevani, M.; Tsiotas, D.; Kolkos, G.; Zafeiriou, E.; Arabatzis, G. Peri-Urban and Urban Green Space Management and Planning: The Case of Thessaloniki, Greece. *Land* **2024**, *13*, 1235. [CrossRef]
24. Ode Sang, Å.; Sang, N.; Hedblom, M.; Sevelin, G.; Knez, I.; Gunnarsson, B. Are path choices of people moving through urban green spaces explained by gender and age? Implications for planning and management. *Urban For. Urban Green.* **2020**, *49*, 126628. [CrossRef]
25. Lovelock, B.; Walters, T.; Jellum, C.; Thompson-Carr, A. The Participation of Children, Adolescents, and Young Adults in Nature-Based Recreation. *Leis. Sci.* **2016**, *38*, 441–460. [CrossRef]
26. Lepoglavec, K.; Papeš, O.; Lovrić, V.; Raspudić, A.; Nevečerel, H. Accessibility of Urban Forests and Parks for People with Disabilities in Wheelchairs, Considering the Surface and Longitudinal Slope of the Trails. *Sustainability* **2023**, *15*, 7741. [CrossRef]

27. Janeczko, E.; Jakubisová, M.; Woźnicka, M.; Fialova, J.; Kotásková, P. Preferences of people with disabilities on wheelchairs in relation to forest trails for recreational in selected European countries. *Folia For. Pol.* **2016**, *58*, 116–122. [CrossRef]
28. Tomczyk, A.M.; Ewertowski, M.W.; White PC, L.; Kasprzak, L. A new framework for prioritising decisions on recreational trail management. *Landsc. Urban Plan.* **2017**, *167*, 1–13. [CrossRef]
29. Schröter, B.; Hantschel, S.; Koszowski, C.; Buehler, R.; Schepers, P.; Weber, J.; Wittwer, R.; Gerike, R. Guidance and Practice in Planning Cycling Facilities in Europe—An Overview. *Sustainability* **2021**, *13*, 9560. [CrossRef]
30. Saunders, R.; Weiler, B.; Scherrer, P.; Zeppel, H. Best practice principles for communicating safety messages in national parks. *J. Outdoor Recreat. Tour.* **2019**, *25*, 132–142. [CrossRef]
31. Deri, M.G.; Chiti, L.; Ciuffoletti, A. A Sustainable Approach to Tourist Signage on Heritage Trails. *Sustainability* **2023**, *15*, 16251. [CrossRef]
32. Yang, T.-H. The effectiveness of information signs in deterring visitor vandalism. *J. Outdoor Recreat. Tour.* **2024**, *45*, 100731. [CrossRef]
33. Kołodziejczyk, K. Networks of hiking tourist trails in the Krkonoše (Czech Republic) and Peneda-Gerês (Portugal) national parks—Comparative analysis. *J. Mt. Sci.* **2019**, *16*, 725–743. [CrossRef]
34. MacLeod, N. The role of trails in the creation of tourist space. *J. Herit. Tour.* **2017**, *12*, 423–430. [CrossRef]
35. Vías, J.; Rolland, J.; Gómez, M.L.; Ocaña, C.; Luque, A. Recommendation system to determine suitable and viable hiking routes: A prototype application in Sierra de las Nieves Nature Reserve (southern Spain). *J. Geogr. Syst.* **2018**, *20*, 275–294. [CrossRef]
36. Chow, J.Y.J.; Hernandez, S.V.; Bhagat, A.; McNally, M.G. Multi-Criteria Sustainability Assessment in Transport Planning for Recreational Travel. *Int. J. Sustain. Transp.* **2013**, *8*, 151–175. [CrossRef]
37. Ravinsky Raichel, N.; Yahel, H. Planning Challenges and Opportunities in the Conservation of National Trails: The Case of the Israel National Trail. *Land* **2024**, *13*, 1449. [CrossRef]
38. Sitzia, T.; Rizzi, A.; Cattaneo, D.; Semenzato, P. Designing recreational trails in a forest dune habitat using least-cost path analysis at the resolution of visitor sight distance. *Urban For. Urban Green.* **2014**, *13*, 861–868. [CrossRef]
39. Denstadli, J.M.; Lindberg, K.; Vistad, O.I. Stakeholder Consensus Regarding Trail Conditions and Management Responses: A Norwegian Case Study. *Scand. J. Hosp. Tour.* **2010**, *10*, 358–374. [CrossRef]
40. Mardani, A.; Zavadskas, E.; Govindan, K.; Amat Senin, A.; Jusoh, A. VIKOR Technique: A Systematic Review of the State of the Art Literature on Methodologies and Applications. *Sustainability* **2016**, *8*, 37. [CrossRef]
41. Amini, A.; Alinezhad, A.; Yazdipoor, F. A TOPSIS, VIKOR and DEA integrated evaluation method with belief structure under uncertainty to rank alternatives. *Int. J. Adv. Oper. Manag.* **2019**, *11*, 171. [CrossRef]
42. Irvanizam, I.; Azzahra, N.; Nadhira, I.; Zulfan, Z.; Subianto, M.; Syahrini, I. Multiple Criteria Decision Making Based on VIKOR for Productive Economic Endeavors Distribution Problem. In Proceedings of the 2021 Sixth International Conference on Informatics and Computing (ICIC), Jakarta, Indonesia, 3–4 November 2021; pp. 1–6. [CrossRef]
43. Ioannou, K.; Tsantopoulos, G.; Arabatzis, G.; Andreopoulou, Z.; Zafeiriou, E. A Spatial Decision Support System Framework for the Evaluation of Biomass Energy Production Locations: Case Study in the Regional Unit of Drama, Greece. *Sustainability* **2018**, *10*, 531. [CrossRef]
44. Xenitidis, K.; Ioannou, K.; Tsantopoulos, G. An innovative methodology for the determination of wind farms installation location characteristics using GIS and Delaunay Triangulation. *Energy Sustain. Dev.* **2023**, *75*, 25–39. [CrossRef]
45. Chang, C.-L. A modified VIKOR method for multiple criteria analysis. *Environ. Monit. Assess.* **2010**, *168*, 339–344. [CrossRef] [PubMed]
46. Wei, J.; Lin, X. The Multiple Attribute Decision-Making VIKOR Method and its Application. In Proceedings of the 2008 4th International Conference on Wireless Communications, Networking and Mobile Computing, Dalian, China, 12–14 October 2008; pp. 1–4. [CrossRef]
47. Opricovic, S.; Tzeng, G.-H. Extended VIKOR method in comparison with outranking methods. *Eur. J. Oper. Res.* **2007**, *178*, 514–529. [CrossRef]
48. Prisner, E.; Sui, P. Hiking-time formulas: A review. *Cartogr. Geogr. Inf. Sci.* **2023**, *50*, 421–432. [CrossRef]
49. Norman, J.M. Running uphill: Energy needs and Naismith's Rule. *J. Oper. Res. Soc.* **2004**, *55*, 308–311. [CrossRef]
50. Hayes, M.; Norman, J.M. Strategy in fell running: An analysis of the Bob Graham Round. *J. Oper. Res. Soc.* **1994**, *45*, 1123–11307. [CrossRef]
51. Costantino, C.; Mantini, N.; Benedetti, A.C.; Bartolomei, C.; Predari, G. Digital and Territorial Trails System for Developing Sustainable Tourism and Enhancing Cultural Heritage in Rural Areas: The Case of San Giovanni Lipioni, Italy. *Sustainability* **2022**, *14*, 13982. [CrossRef]
52. Lukoseviciute, G.; Henriques, C.N.; Pereira, L.N.; Panagopoulos, T. Participatory development and management of eco-cultural trails in sustainable tourism destinations. *J. Outdoor Recreat. Tour.* **2024**, *47*, 100779. [CrossRef]
53. Winter, P.L.; Selin, S.; Cerveny, L.; Bricker, K. Outdoor Recreation, Nature-Based Tourism, and Sustainability. *Sustainability* **2019**, *12*, 81. [CrossRef]
54. Lekies, K.S.; Whitworth, B. Constructing the Nature Experience: A Semiotic Examination of Signs on the Trail. *Am. Sociol.* **2011**, *42*, 249–260. [CrossRef]
55. Apostolidis, G. Indicators for sustainable tourism management: A case study using AHP and Delphi to evaluate mountainous areas in Greece. *Int. J. Agric. Resour. Gov. Ecol.* **2022**, *18*, 100. [CrossRef]

56. Stoffelen, A. Tourism trails as tools for cross-border integration: A best practice case study of the Vennbahn cycling route. *Ann. Tour. Res.* **2018**, *73*, 91–102. [CrossRef]
57. Tampekis, S.; Kantartzis, A.; Arabatzis, G.; Sakellariou, S.; Kolkos, G.; Malesios, C. Conceptualizing Forest Operations Planning and Management Using Principles of Functional Complex Systems Science to Increase the Forest's Ability to Withstand Climate Change. *Land* **2024**, *13*, 217. [CrossRef]
58. Kolkos, G.; Stergiadou, A.; Kantartzis, A.; Tampekis, S.; Arabatzis, G. Effects of forest roads and an assessment of their disturbance of the natural enviroment based on GIS spatial multi-criteria analysis: Case study of the University Forest of Taxiarchis, Chalkidiki, Greece. *Euro-Mediterr. J. Environ. Integr.* **2023**, *8*, 425–440. [CrossRef]
59. Ballantyne, M.; Pickering, C.M. The impacts of trail infrastructure on vegetation and soils: Current literature and future directions. *J. Environ. Manag.* **2015**, *164*, 53–64. [CrossRef]
60. Marion, J.L. Trail sustainability: A state-of-knowledge review of trail impacts, influential factors, sustainability ratings, and planning and management guidance. *J. Environ. Manag.* **2023**, *340*, 117868. [CrossRef]
61. Fleckhaus, P.; Heldt, T. *Sustainable Recreational Trails in Sweden: Is It Possible to Talk About ROI for Hiking Trail Investments?* CeTLeR—Centre for Tourism and Leisure Research; Tourism Studies; Dalarna University: Borlänge, Sweden, 2022; p. 45.
62. Tomczyk, A.M.; Ewertowski, M. Planning of recreational trails in protected areas: Application of regression tree analysis and geographic information systems. *Appl. Geogr.* **2013**, *40*, 129–139. [CrossRef]
63. Yan, Z. TODIM-VIKOR method for quality evaluation of tourism rural landscape planning and design with 2-tuple linguistic neutrosophic numbers. *J. Intell. Fuzzy Syst.* **2023**, *45*, 8249–8261. [CrossRef]
64. Ioannou, K.; Tsantopoulos, G.; Arabatzis, G. A Decision Support System methodology for selecting wind farm installation locations using AHP and TOPSIS: Case study in Eastern Macedonia and Thrace region, Greece. *Energy Policy* **2019**, *132*, 232–246. [CrossRef]
65. Arabatzis, G.; Kolkos, G.; Stergiadou, A.; Kantartzis, A.; Tampekis, S. Optimal Allocation of Water Reservoirs for Sustainable Wildfire Prevention Planning via AHP-TOPSIS and Forest Road Network Analysis. *Sustainability* **2024**, *16*, 936. [CrossRef]

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Review

Rethinking the Smart Green City Project in South Korea: A Critical Juncture Approach

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Abstract: Over the past 10 years, the Korean government has declared its intention to achieve carbon neutrality to the international community and strived to create smart cities and green cities as a practice to achieve carbon neutrality. In the same context, the Smart Green City project, which began in earnest at the end of 2020, initially attracted national attention due to the strong will of the administration. However, limitations in its performance were revealed. This study aimed to identify the policy mechanisms that led the Korean government to pursue the Smart Green City project using a critical juncture approach and to derive useful implications for policy selection. A critical juncture framework was applied for in-depth analysis, and a descriptive case study based on critical thinking was conducted. The results confirmed that endogenous and exogenous environmental changes surrounding the government at critical junctures were mechanisms for establishing the Smart Green City project. In addition, the government's attempt to differentiate itself from the policies of previous governments was confirmed to be a constraint that actually hindered the project's progress. This study concludes that if a government facing a complex crisis makes hasty policy decisions, it is likely to repeat the policy pattern or institutional path of previous governments. It also argued that in this situation, policy choices that aim to cut a new path may cause the government to choose a wrong path, which may have irreversible consequences.

Keywords: smart green city; smart city; green city; smart sustainable city; carbon-neutral city; critical junctures

1. Introduction

Despite the frequent occurrence of disasters and calamities due to global warming, the world has neglected this threat because the effects of climate change are neither immediate nor direct. Fortunately, the world has recently recognized climate change as a collective action problem in urgent need of redress, with mounting global cooperation efforts emerging to achieve this [1]. For example, at the 17th Conference of the Parties to the United Nations Framework Convention on Climate Change held in Durban, South Africa, in 2011, an international agreement was reached to impose greenhouse gas reduction obligations on all parties from 2020. This initiative required the comprehensive promotion of greenhouse gas reduction policies in all sectors, from the industrial and transportation sectors to the non-industrial sector. In December 2014, the 20th General Assembly held in Lima, Peru, agreed on each country's Intended Nationally Determined Contribution (INDC) for 2020 and beyond, and 162 countries—including 28 European Union countries—submitted their national contributions to the international community. Regarding the main contents of the submission, the 28 EU Member States, Norway, and Switzerland presented the goal of reducing emissions by 40–50% compared to 1990 levels by 2030, while Mexico aimed to reduce emissions by 25–40% compared to normal by 2030 [2]. Further, in accordance with the Green Deal established in 2019, the European Union has recently planned to implement the Carbon Border Adjustment Mechanism (CBAM) in earnest from 1 January 2026, after a transitional phase starting in 2023 [3]. The United States has also planned to invest

large amounts of money in real energy security and climate change response through the implementation of the Inflation Reduction Act (IRA) in 2022. In contrast, developing countries are in a difficult position due to the enormous economic burden imposed by carbon emission regulations as well as the lack of emission reduction technology that can respond to these strong measures by the EU and the US [4,5]. In the meantime, the energy outlook by IEA predicted that the global demand for coal, oil, and gas will peak in 2030 and then decline, and that the transition to clean energy will proceed faster than expected [6–8]. These global energy trends could ultimately have a significant impact on key policy decision making in each country, including industrial investment, trade flows, electrification, and energy access.

Major countries around the world have been steadily attempting to transition to a low-carbon economic structure. In Korea, the Lee administration launched the presidential "Green Growth Committee" in 2009, to establish an international-level greenhouse gas management system, and enacted the "Framework Act on Low Carbon, Green Growth" initiative in 2010. The Park administration completed the implementation of the greenhouse gas emissions trading system in 2015, and established a greenhouse gas and energy target management system. The Moon administration subsequently designated companies that emit a lot of greenhouse gases and consume a lot of energy as management companies and asked them to pursue and fulfill reduction goals [9,10]. However, Korea has been labelled a "climate villain" by the international community in recent years. In 2023, Korea ranked 60th among 64 countries on the Climate Change Performance Index (CCPI). Korea is also the world's ninth largest energy consumer and ranks seventh in terms of highest greenhouse gas emissions [11–13]. To date, the Korean government has built infrastructure for the establishment of a low-carbon economic system, but failed to monitor its implementation. The promise of carbon reduction was not maintained, and carbon emissions increased [14].

On the other hand, based on the Green New Deal, the Moon administration established Korea's unique Smart Green City project, which aims to create a carbon-neutral city and achieve the green transformation of the city through local government participation from 2021 to 2022 [15–18]. However, previous governments have also been pursuing similar projects, and the United Nations (UN) and the United Nations Educational, Scientific and Cultural Organization (UNESCO) have already emphasized the need to address the climate and environmental crisis and promote the sustainable transformation of cities [19]. In addition, due the joint promotion of U4SSC by UNECE and ITU, a Smart Sustainable City (SSC) initiative that has been combining smart cities and green cities since 2016, questions need to be raised about the fundamental background of the Korean government and their promotion of a separate Smart Green City project similar to it [20,21].

Unfortunately, despite the support of the President, the Smart Green City project, in which approximately KRW 290 billion (approximately USD 210 million) was invested over two years and 25 local governments participated, did not achieve any results [15]. Then, in relation to this, criticisms poured out, such as the short project implementation period, the lack of use of smart technologies including ICT, and poor consideration of the friction between the project and existing urban planning [22–26].

In this context, this study inferred that the Korean government's Smart Green City project may be the result of a combination of related projects promoted by previous governments. It is assumed that attempts to obtain quick results in a short period of time ultimately yielded no results. Based on these inferences and assumptions, this study focuses on the mechanism that led to the full-scale promotion of the Smart Green City project, and to solve these questions, it traces the roots of the Smart Green City project in a historical and institutional context and identifies the crucial changes that occurred before the project began.

This study seeks to reflect the critical juncture framework of historical institutionalism as a methodology for in-depth analysis. Historical institutionalism has been used in comparative social science research for over 60 years. The key concepts of this methodology include path dependence, historical context, and critical junctures. This perspective ex-

plains policy phenomena by identifying how institutions form and operate. In political and policy processes, the scope of policy actors' choices depends on the institutional framework, and policies emerge as a result of the interactions between policy actors within this institutional framework. In other words, policies are viewed as products of institutions. Once institutions are formed, they follow specific paths and exhibit path dependence, whereby policy patterns are maintained. As past choices limit the scope of future choices, it becomes increasingly difficult to deviate from existing paths over time. A critical juncture is the point of choice between two or more alternatives when a particular option is adopted. It is useful for explaining both (1) the historical origin and maintenance of social order and (2) the occurrence of social change through sudden and large leaps [27,28].

While institutions change gradually, they can undergo rapid transformation in response to exogenous and endogenous environmental changes. Therefore, the critical junctures at which social relations and institutions are reshaped in response to political, economic, and environmental crises and challenges are significant for the study of policy change. The critical juncture framework is a theory of institutional emergence and change, and a well-developed set of research methods for analyzing institutional change from a comparative perspective. This methodology has proven effective for identifying the cause of policy change because it emphasizes the role of actors, events, and institutional contexts in creating lasting institutions [29,30].

On the basis of this theoretical framework, this study examines whether past institutional contexts and path dependences influence the initiation and subsequent performance of Smart Green City project at critical junctures. Therefore, the goal of this study is to use a critical juncture approach to identify the mechanism of policy change that led the Korean government to fully pursue the Smart Green City project, and to derive useful implications for future policy choices.

This paper comprises five sections. The introduction section raises the issues of the Smart Green City project, which was launched while Korea was still unable to escape the stigma of being a "climate villain", and presents the research purpose. The literature review section provides a theoretical review of historical institutionalism, path dependences and critical junctures. The third section, comprising the research methodology, covers research frameworks and questions based on the critical juncture framework and provides a case study. The next section presents the results of the analysis, which are divided into the following elements, presented in a table: antecedent conditions, permissive conditions, critical junctures, reactive sequences, counter reactions, outcomes and a summary of the findings. Finally, the discussion section summarizes the main arguments, synthesizes the policy mechanisms and suggests useful implications for future policy choices.

2. Literature Review

2.1. Historical Institutionalism and Path Dependence

Historical institutionalism emerged in the 1970s, when comparative political scientists sought a methodology able to explain policy differences between countries [31–33]. In particular, it quickly emerged as a major approach in the social sciences, amid growing critical awareness of behaviorism and its potential as an alternative. Under historical institutionalism, institutions establish patterns of human behavior over a long period and act as an external constraint on the behavior of individuals or groups. Institutions also constrain the government's ability to formulate and implement policy, and both delimit the actions of and provide opportunities for political and economic actors [34–36]. Historical institutionalism has been used to analyze political, economic, and social processes as interactions between actors and structures under institutional constraints. In other words, the approach focuses on whether institutions shape the power, interests, preferences, and behaviors of actors in relation to other actors [37–40].

As a comparative research methodology, it emphasizes the use of institutions, history, and context as variables that explain policy formation and the differences between countries. Contending that different institutions, histories, and contexts lead to differ-

ences in policy, this qualitative analytical approach derives similarities and differences between policies by examining the history and context of policy case studies based on the existing literature. Moreover, because it focuses on vertical and horizontal institutions and institutional contexts in which individual policies are implemented, and adopts a historical approach to explain such institutional contexts, historical institutionalism can explain the administrative phenomena that appear in accordance with the social, political, and economic systems of a specific country.

The core concept of historical institutionalism, path dependence, refers to the causal influence of early historical events on the development of later events. Once a policy or institution enters a specific path, it rarely deviates from that path, even if the path is later recognized as inefficient. Therefore, path dependence is a process wherein past choices limit the scope of future choices and is characterized by the fact that decision making is connected in a time series [41]. As Table 1 shows, there are two major types of path dependence: self-reinforcing and reactive. Self-reinforcing sequences indicate that policies are continuously reproduced without change. They represent a set of forces or processes that reproduce a particular pattern of events, choices, or activities over time, making it difficult to abolish existing policies. Self-reinforcing sequences can be classified into increasing returns, negative feedback, and cyclical processes. Increasing returns refer to the continuous maintenance or reproduction of the same institution or policy. As the selection and maintenance of a path operates based on a different logic, the path continues even if the actor who chooses the path disappears at a critical point. Path reproduction mechanisms cement a given pattern, ensuring effective reproduction and making it very difficult to abolish. Negative feedback refers to the balancing process as a path unfolds. After the flow appears to deviate from the path for a period of time, negative feedback effects bring the path back into balance. Cyclical processes refer to the occurrence of a cycle between two alternatives.

Table 1. Types of path dependence.

Classification		Description
Reinforcing Sequences	Increasing Return	The maintenance and reproduction of existing institutions and policies
	Negative Feedback	Mechanism of balancing procedure as the path unfolds
	Cyclical Processes	Circulation between two alternatives
Reactive Sequences		The formation of one path as plural events are connected under necessary and sufficient conditions

Source: Mahoney (2000) [24], Bennett and Elman (2006) [39].

Meanwhile, reactive sequences are formed by the accidental combination of several events, which then cause the subsequent event [27,42]. In this sequence, multiple events intersect accidentally in conjunctures, causing subsequent events; these result in a chain of reactions that form a single path of temporally ordered and causally linked events. For events to be dependent on the reactive path, the initiating historical event must be a coincidental combination, and the overall chain of events must have inherent sequentiality. Self-reinforcing sequences are characterized by regenerative processes that reinforce the initial event, while reactive sequences are characterized by repulsive processes that transform and possibly reverse the initial event [27]. However, reactive sequences in the critical juncture period are likely to vary in their capacity to disrupt, transform, or reproduce the institutional outcomes of the critical junctures themselves. Some outcomes may be reinforced or "locked in" by reactive sequences that they effectively channel, creating path-dependent institutional legacies. Others may be transformed by reactive sequences that disrupt initial outcomes and create long-term institutional legacies that sharply diverge from them [40,43].

According to Pierson, the following four factors cause path dependence in institutions and policies. The first is large set-up or fixed costs. In this regard, when actors make a large investment in a specific system, they will try to maintain the system to recover the costs. The second factor is learning effects. When actors work for a long time in a system that moves along a specific path, they become familiar with the system and gain more knowledge, and thus continue maintaining the system for the sake of system efficiency. The third factor is coordination effects, that is, the benefits that a set of actors can gain from following a specific path increase when other actors adopt the same path. The fourth is adaptive expectation, which refers to the fact that when other competitors expect to follow a certain path, they choose an alternative to avoid falling behind [35].

Mahoney proposed the following four explanations of path dependence. The first is the utilitarian explanation, whereby actors ultimately pursue efficiency and rationally reproduce the institution from a cost–benefit perspective. Institutional change occurs when actors who pursue rational self-interest are unable to reproduce a given institution. The second, the functional explanation, holds that institutions are created because of the benefits they will produce. In other words, if a specific institution is adopted because of an accidental event, the adopted institution contributes to the specific function of the system, which leads to the expansion of the institution, strengthening its capacity and ultimately hardening it. Third, the power explanation is similar to the utilitarian explanation in that it assumes that actors make decisions based on cost–benefit. However, it differs in contending that, if the institution distributes costs and benefits unfairly, it will continue if the elite group that benefits from the existing institution has sufficient power to maintain it. Finally, the legitimization explanation holds that the reproduction of an institution is based on the actor's trust in what is right. In this scenario, an institution is path dependent because actors consider it justified and reproduce it voluntarily. Therefore, even if the previous institution had greater legitimacy, the original institution is strengthened because the preferred institution becomes the standard for assessing legitimacy [27].

Meanwhile, Thelen explained the factors of path dependence in terms of layering and conversion. Although the purpose of layering does not change significantly, some elements of the existing policy are partially changed. Conversion refers to a major change in the role and function of existing policies for new purposes [44]. Table 2 summarizes the factors of path dependence according to Pierson, Mahoney, and Thelen.

Table 2. Factors of path dependence identified by Pierson, Mahoney, and Thelen.

Scholars	Factors
Pierson (2000) [32]	Large set-up or fixed costs Learning effects Coordination effects Adaptive expectation
Mahoney (2000) [24]	Utilitarian explanation Functional explanation Power explanation Legitimation explanation
Thelen (2003) [44]	Layering Conversion

2.2. Critical Junctures

Theorizing about critical junctures began in the social sciences in the 1960s. Since then, it has become a mainstay of historically informed social science research. Historical institutionalists emphasize the continuity of institutions and highlight path dependence and unintended consequences when explaining institutional change and development. The theoretical framework of critical junctures is centered on the idea that critical turning points are major macro-level change episodes that produce a lasting legacy. Closely associated with comparative historical research and qualitative methods, the concept of critical junc-

tures has been applied to case studies on a wide range of topics, including state formation, political systems and democracy, party systems, public policy, government performance, economic development, and cultural norms [45,46].

As seen in Section 2.1, path dependence does not mean the "stagnation" or "fixation" of a path, but a differentiated and self-reinforcing path of institutional development. In this process, critical junctures, that is, "turning points" where the institutional development path diverges, are significant. Not all institutions are products of critical junctures. After all, they sometimes develop gradually, and their specific starting points are not always identifiable. However, if major institutional changes occur over a relatively short period, they can be assumed to be influenced by a critical juncture [28].

Historical institutionalism emphasizes external shocks or crises as factors of institutional change. The occurrence of a critical juncture or specific event in an existing institution results in uncertainty. In this situation, various options, such as drastic institutional change, may be presented. During such periods of uncertainty, key actors must choose from several alternatives to create a long-lasting legacy. Therefore, to identify the institutional changes and consequences resulting from critical junctures, it is necessary to understand antecedent and permissive conditions [47].

Antecedent conditions refer to the pre-critical juncture period and historical factors encompassing the diverse features of the economy, society, and politics that constitute the parameters of subsequent change. Permissive conditions can be defined as factors or conditions that change the underlying context to increase the causal power of agency or contingency, shaping the prospects for divergence. In this process, the mechanisms involved in the reproduction of the previous critical juncture are undermined, creating a new context in which divergence from the previous stable pattern can emerge [28,45].

3. Research Methodology

3.1. A Critical Juncture Framework as a Methodology

To examine the process and causes of change occurring at critical junctures in Korea's Smart Green City project, this study adopts Sorenson's critical juncture framework, which is used for the causal analysis of rapid institutional changes. In Sorensen's critical juncture framework, historical events unfold according to historical sequence. Sorensen proposed the critical juncture framework for examining the change process of urban planning, advancing its value for the causal analysis of theoretical explanations and institutional change processes [28]. In the critical juncture framework, a critical juncture is the point at which an option is selected from two or more possibilities and a diverging or developmental path begins. In particular, a critical juncture is important because once one of the various alternatives is selected, it is difficult to return to the starting point. Sorensen explained that a critical juncture can be defined as a period of significant change that occurs in a distinct way in a country or subunit of analysis, creating a distinct legacy. He argued that critical junctures are caused by a crisis that undermines the legitimacy of existing institutions, making it possible to reorganize them and create new ones [28].

As such, this study analyzed the change process of the Smart Green City project in Korea using Sorenson's analysis structure as a framework. The conceptual definitions of each stage are as follows. (1) Antecedent conditions: These are historical factors that structure the available options and choices at a critical juncture [46]. In this regard, this study investigated the Smart City project promoted before the Smart Green City project in the pre-critical juncture, as well as the Low-Carbon, Green Growth strategy, as antecedent conditions. (2) Permissive conditions: These are factors that permit major changes to institutions or policies, that is, the "cleavage" or "crisis" events that enable institutional change and trigger the critical juncture [46]. This study identified the crisis in political leadership and the emergence of Sustainable Smart City initiatives as permissive conditions. (3) Critical junctures: Shaped by productive conditions, a critical juncture refers to the moments or events that provide an opportunity for institutional change. The productive conditions take into account the antecedent factors of a specific case, the key actors, the

institutional context, and the order of institutional development. In this respect, the critical juncture is the moment in which a new institution or policy (the "legacy") is selected from among multiple possibilities through "mechanisms of production" and becomes path dependent because of "mechanisms of reproduction" [27,47,48]. In this respect, this study focused on the external pressure on the international community's climate crisis response plan and the context that led to the formation of the Smart Green City project according to the beliefs of the political leadership during the critical juncture. (4) Reactive sequence: This refers to sequences of reactions and counter reactions to major changes. It is a reactionary process that transforms and reverses initial events. For this stage, this study investigated the central government's reaction and the local government's counter-reaction in the process of promoting the Smart Green City project. (5) Outcome: The final stage involves the resolution of conflicts over changes made during the critical juncture. This study explored the results of a Smart Green City project promoted by local governments.

3.2. Case Study Approach

3.2.1. Research Questions and Methods

The research framework in Figure 1 illustrates the key analytical elements and research flows implemented by the government within the research timeframe related to the Smart Green City project, based on Sorensen's critical juncture framework.

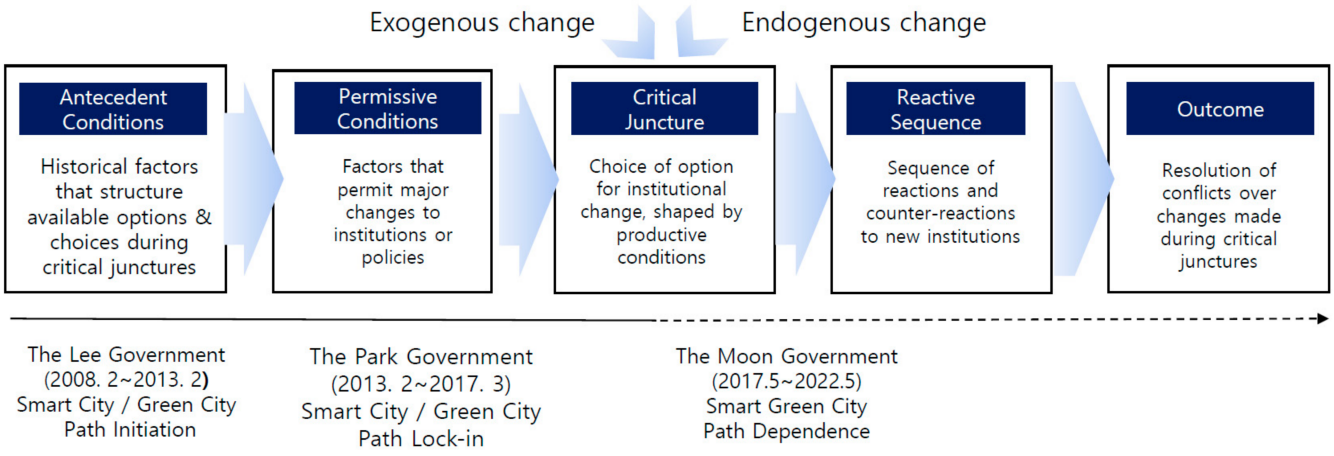


Figure 1. Research framework. Source: Author's Summary.

This study aims to identify the policy change mechanism that led the Korean government to fully promote the Smart Green City project. Accordingly, based on the literature review, the research questions addressed in this paper are as follows:

- How does the Smart Green City project relate to the institutional context of previous governments' smart city and green city policies?
- What role, from the perspective of critical junctures, did the Moon administration play in the birth of the Smart Green City project, and how could the institutional context, key actors, and events be explained?
- What is the path dependence of the Smart Green City project on the relevant policies of previous governments?
- What are the features of relevant policy changes before and after the launch of the Moon administration's Smart Green City project?

Moreover, it employs a descriptive case study method and reviews domestic and international literature related to the Smart Green City project and critical junctures. In other words, literature, statistics, and web documents related to the Smart Green City, smart sustainable city, green city, and ubiquitous city (U-city) published by domestic and international organizations are collected and reviewed. Unlike empirical research, this descriptive case study method focuses on "what is" and "what was" rather than answering the "why" and "how". Therefore, this study emphasizes the identification of variables and

observations based on critical thinking, and analyzes the current situation by reviewing and evaluating past problems and solutions.

Briefly, this study focuses on the Smart Green City project in Korea; deals with two conceptual topics, the smart city and green city, considered to be related to the emergence of the Smart Green City project; and examines the process of change in related policies. In this paper, a smart city is defined as a platform city that improves the quality of life of citizens, strengthens the sustainability of the city, and fosters new industries by utilizing innovative technologies of the Fourth Industrial Revolution [49]. A green city, also called an eco-city or sustainable city, is a city in which the environment and economy coexist, reorganizing all urban structures into a low-carbon system to respond to environmental conservation and climate change, and creating jobs and new growth engines to promote economic growth [50,51]. A U-city is defined as an environmentally friendly and sustainable smart (or knowledge) city that makes ubiquitous computing available to urban elements such as people, buildings, infrastructure and open space [52]. From the perspective of the Smart Green City project, a smart green city is a future environmental city that increases climate resilience, uses resources and energy efficiently, and minimizes pollutant emissions based on local leadership and resident participation to transform the city into an economically prosperous and green city [17].

The temporal scope is set from 2008 to 2022, that is, from when the Lee Myung-bak administration was launched, through the Park Geun-hye administration, to when the Moon Jae-in administration left office.

3.2.2. Overview of Korea's Smart Green City Project

Led by the Ministry of Environment, Korea's Smart Green City project sought to mitigate the threat of the climate and environmental crisis. Indeed, 91.8% of the Korean population lives in cities, and greenhouse gas emissions have reached 75% [53–55].

Korea, which showed a low CCPI in overall sectors, ranked very low in the CCPI greenhouse gas emissions and energy use sectors, and also low in the renewable energy and climate policy sectors [11]. Ironically, as shown in Figure 2, Korea's CCPI greenhouse gas emissions decreased slightly before the launch of the Smart Green City project in 2020, but began to increase again in 2021 when the project actually began; its ranking in CCPI by country also fell from 60th in 2023 to 64th in 2024 [56,57].

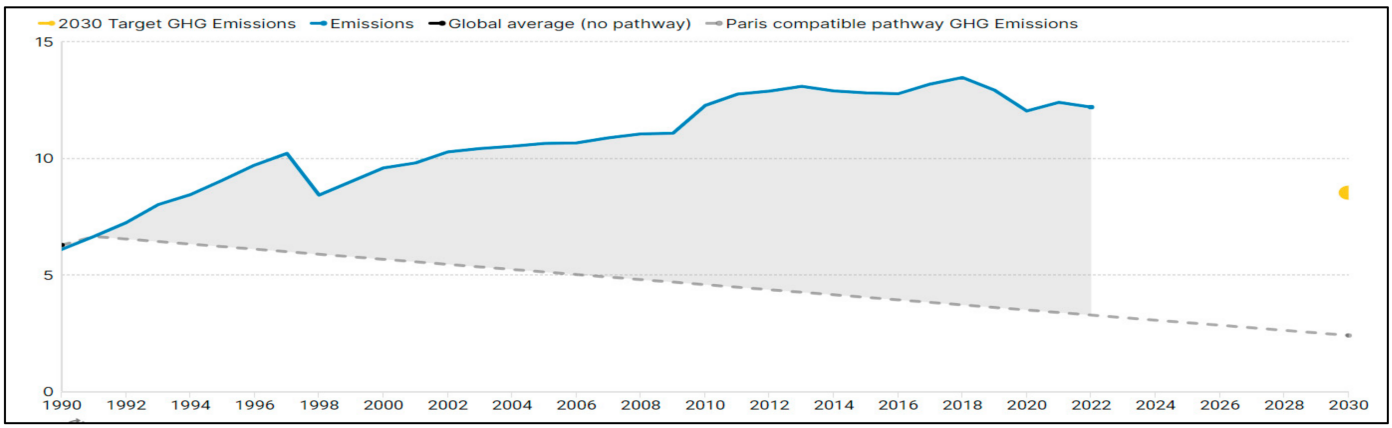


Figure 2. Korea's GHG emissions per capita (CO2 eq., incl. LULUCF). Source: Climate Change Performance Index (CCPI). 2024 [52].

As Figure 3 shows, according to a Ministry of Environment press release, the project envisioned a sustainable "future environmental city" where humans and nature coexist [17,58]. In this regard, a future environmental city refers to the transformation of a city into an economically prosperous and green city by increasing climate resilience, using resources and energy efficiently, and minimizing pollutant emissions based on local leadership and

resident participation. Here, the transition to a green city is understood as the transition from a growth-driven society to an ecological and environmentally sustainable society.

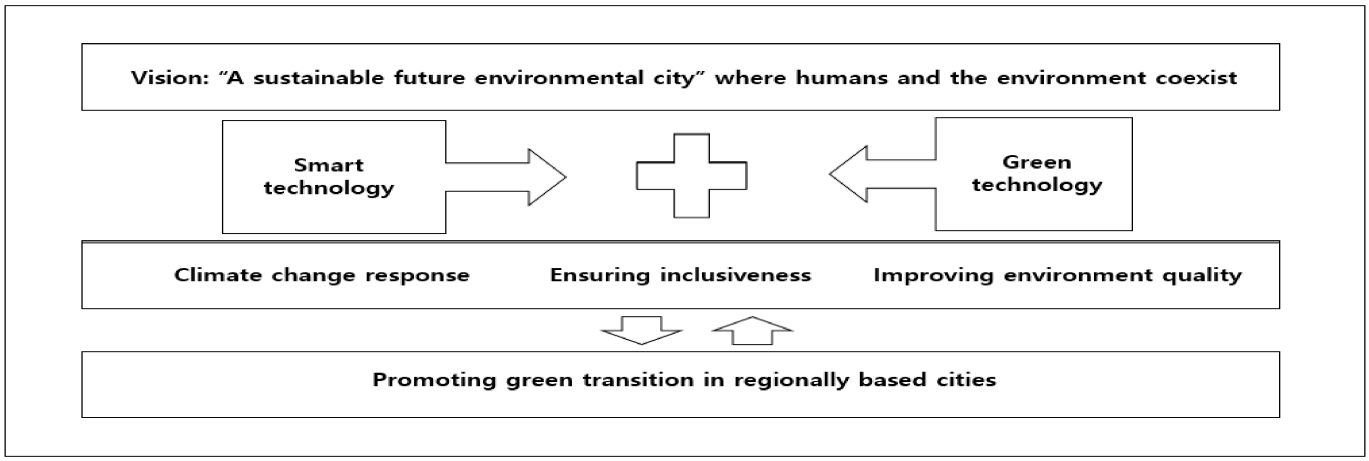


Figure 3. Vision of Smart Green City Project. Source: Ministry of Environment. Press Release. 2020 [17,58].

More specifically, the Smart Green City project identified the following goals:

- Climate change response: Achieve carbon neutrality in order to lay the foundation for a climate-resilient society.
- Inclusiveness: Enhance trust and cohesion through community participation.
- Enhancement of environmental quality: Achieve ecological conservation and a reduction in pollutant emissions based on human–nature symbiosis.

In this context, "green" refers to a traditional method of improving the environment, while "smart" refers to a new and innovative method of improving the environment. The principle of the project is that the region, that is, the local government, should proactively prepare measures to enhance environmental performance to improve the sustainability of urban green transformation, and that the central government should provide financial support, discover innovative projects, and serve as a platform for the expansion of the project.

The Smart Green City project is a representative project for "recovering the city's green ecosystem" among the eight tasks of the Green New Deal announced by Moon's administration. A public offering period of approximately 80 days was set from September 2020, with the project open for public offering until the end of December of that year. Of the project plans submitted, a total of 25 target areas were selected. The total project cost approximately KRW 290 billion (approximately USD 209.9 million), of which 60%—that is, KRW 170 billion (approximately USD 123 million)—was invested by the national treasury, while the remaining 40% (KRW 120 billion, or approximately USD 86 million) was invested by local funds.

As Table 3 shows, the project was divided into four major implementation areas, comprising ten climate and environmental business types.

Table 3. Business types included in the Smart Green City Project Guidelines.

Dimension	Resilience			Low Emissions		Ecological Restoration			Human-Centered	
Basic direction	Build urban resilience to respond to climate change			Establish low-emission support infrastructure to reduce greenhouse gases		Restore the urban ecosystem to preserve and restore the natural environment and enhance accessibility			Improve living conditions, including environmental education and the protection of vulnerable groups	
Business type	①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩
	Climate elasticity	Water circulation	Water safety	Future car	Resource circulation	Ecological restoration	Ecological rest	Clean atmosphere	Environmental education	living conditions

Source: Ministry of Environment. Press Release. 2020 [17,58].

In particular, as Figure 4 shows, the project recommended spatial and organic linkages between business types with the potential to create synergies by utilizing applicable smart technologies; this included for example, creating co-benefits by linking environmental issues and smart technologies.

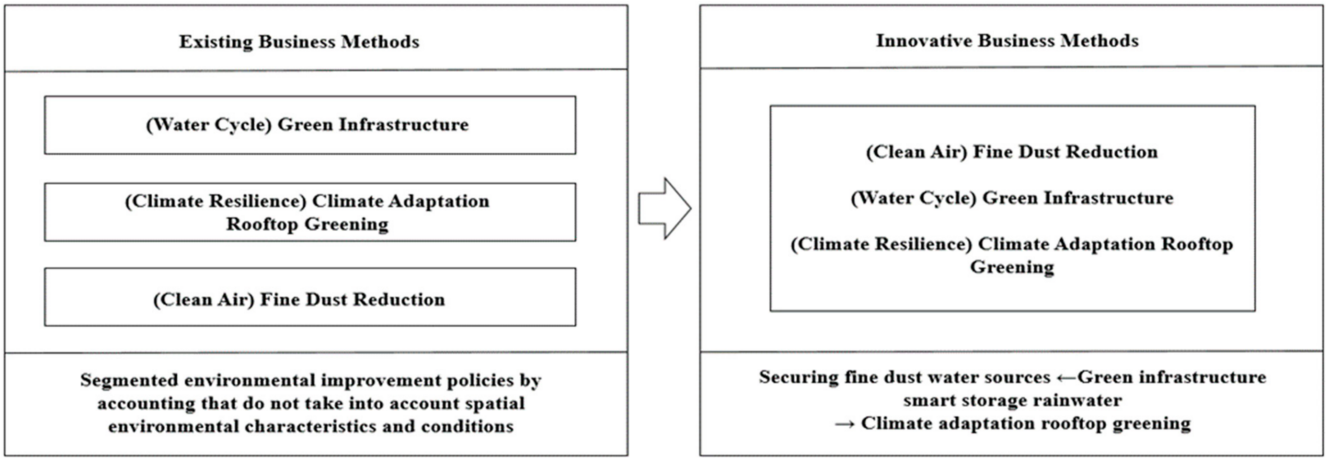


Figure 4. Business methods in the Smart Green City Project. Source: Ministry of Environment. Press Release. 2020 [17,58].

Table 4 presents the two Smart Green City business models. Specifically, the "common model" aimed to create a ripple effect at the community level by combining two or more business types to solve climate problems. If selected, each local government could receive up to KRW 10 billion (approximately USD 7.24 million) in support over a period of two years. Meanwhile, the "general leading model" provided support of up to KRW 16.7 billion (approximately USD 12 million) over a two-year period to each selected local government. This model advocated for the combination of three or more business types with the goal of actively greening urban spaces beyond the community. In both models, regions (local governments) led the project.

Table 4. Common model vs. general leading model.

Category	Common Model	General Leading Model
Main purpose	Local-led solutions to climate and environmental issues	Local-led climate and environmental problem solving + green transition
Applicable unit	Community	Community or more
Number of the linked business types	Combination of 2 or more of 10 business types	Combination of 3 or more out of 10 business types
Selection scale	Around 20 locations	Around 5 locations
Scale of support	Up to KRW 10 billion/2 years	Up to KRW 16.7 billion/2 years

Source: Ministry of Environment. Press Release. 2020 [17,58].

Furthermore, the Ministry of the Environment ran a "Smart Green City Support Group" during a contest period to provide advice and help local governments prepare their business plans. The Green City Support Group was supposed to be limited to agencies under the Ministry of the Environment, with no other participating ministries [17].

4. Results

4.1. Antecedent Conditions

4.1.1. The Lee Government's Low Carbon, Green Growth Strategy

Upon commencing his five-year term in February 2008, President Lee promoted a green growth and ubiquitous strategy. In 2008, he proposed a low-carbon green growth

strategy as a new national growth engine in his National Liberation Day speech. This strategy sought to advance Korea's economic and industrial structure by combining the two values of the environment (green) and growth using green technology, further developing technology, and encouraging the adoption of low-carbon lifestyles [59–61].

However, due to the occurrence of the global financial crisis after the announcement of the aforementioned strategy, the Lee administration promoted the Green New Deal as a means of overcoming the domestic economic crisis. The Green New Deal sought to restore the four major rivers, develop new and renewable energy, improve energy efficiency, and expand the green transportation network. It became the cornerstone of Korea's strategy to overcome the financial crisis and received considerable attention when it provided valuable insights for member countries at the G20 Summit held in London in April 2009 [9]. The Lee government subsequently launched the Presidential Green Growth Committee and enacted the world's first "Framework Act on Low Carbon, Green Growth" in December 2010. The law aimed to establish the foundation necessary for low-carbon green growth and promote the development of the national economy by utilizing green technologies and industries that minimize greenhouse gas and pollutant emissions. It also specified that the government must establish a low-carbon, green growth national strategy to address climate change, energy, and resource issues; expand growth engines; ensure the efficient use of land; and create a pleasant environment [62]. The law affirmed the state's commitment to taking responsibility for global issues. That said, the law contained no expression or explanation of the term "green city" [63].

The Lee government emphasized the three elements of strategy, technology, and financial resources to support and promote green growth as a global architecture. To this end, the government established the Global Green Growth Institute (GGGI) and Green Technology Center (GTC) [64]. Led by the Korean government, the GGGI was officially promoted at the 2012 United Nations Conference on Sustainable Development—also known as Rio + 20—as a treaty-based intergovernmental organization supporting sustainable economic growth in developing countries and emerging economies based on the principles of social inclusion and environmental sustainability [65].

The Green Climate Fund (GCF) was established at the 16th Conference of the Parties on Climate Change (COP 16) held in Cancun, Mexico, in December 2010, and Korea subsequently hosted the GGGI and GCF headquarters in Seoul and Songdo, respectively [66]. Launched in February 2009, the Presidential Green Growth Committee played a key role in reviewing, inspecting, and evaluating major policies related to national low-carbon and green growth, and the establishment of a five-year Green Growth Plan during the President's five-year term.

4.1.2. The Ministry of Land, Transport and Maritime Affairs' U-City Project and the Invisible Smart Green City Under the Lee Government

The predecessor of the smart city, the concept of the ubiquitous city or "U-city", emerged as a topic of discussion in Korea in the late 1990s, and finally came to fruition in 2008, with the enactment of the Ubiquitous Act by the Lee administration [67].

Exemplified by Songdo city, the concept of the U-city predates that of the smart city in Korea. Unlike smart cities, which focus on connectivity inside and outside the city, the U-City focuses on the completeness of the unit city using ubiquitous technology. As the department in charge of the U-city project, the Ministry of Land, Transport, and Maritime Affairs announced their comprehensive plans for a first and second U-city in 2009 and 2014, respectively. The U-city project initially aimed to innovate all aspects of the city, including increasing the convenience of urban life and improving quality of life, safety, and citizen welfare by utilizing ubiquitous information technology. However, issues related to climate change and the global environmental crisis were not addressed.

The Ministry of Land, Transport, and Maritime Affairs also addressed the concept of the green city, that is, a basic spatial unit that improves the quality of life of city residents by reducing and absorbing the greenhouse gases emitted from industry, buildings, and

transportation. Meanwhile, the Ministry of Environment defined a green city as a city that drives green growth by reducing greenhouse gases and environmental pollution, and creating jobs as a new growth engine by reorganizing urban infrastructure and lifestyles into low-carbon ones [68]. However, at that time, research on the technological application of green cities had only been conducted at research institutions and had yet to undergo comprehensive planning and implementation. It thus emerged as an antecedent condition for the Smart Green City project [69,70].

4.2. Permissive Conditions

4.2.1. The Park Government's Creative Economy Strategy and the Phasing Out of Lee's Green Growth Strategy

After taking office in February 2023, the Park administration replaced the previous government's national vision of green growth with one championing a "creative economy". Indeed, green growth virtually disappeared at the beginning of Park's term. The Framework Act on Low Carbon and Green Growth was revised, and the status of the Green Growth Committee—a legal deliberation body that was as a key actor in the previous government's green policy—was reduced from a body under the president to one under the prime minister. Although the Lee government secured a powerful position internationally in the fields of climate change and green growth, it suffered political difficulties domestically throughout its term because of issues with the Four Major Rivers Project. As such, there was little reason for Park's government to continue its legacy [71,72].

In contrast to its predecessor, the Park government focused its climate policy on promoting a creative economy and fostering low-carbon technology-based industries combining cutting-edge science and technology with ICT. During her term, President Park established the Second Five-Year Green Growth Plan and the National Energy Basic Plan, which aimed to reduce national greenhouse gases and revitalize renewable energy. Unable to ignore climate issues at the global level, the Park administration prepared Korea's NDC when the Paris Agreement was adopted in 2015 and came into effect in 2016. As part of these efforts, Korea intends to reduce greenhouse gas emissions by 55 million tons by 2030. Notably, Korea increased its installed solar PV capacity to more than 1 GW by 2015, with the country ranking seventh in the world during Park's presidency [73].

Overall, green growth was not a major national task for the Park administration, and appears to have been used as a response tool to revive the energy industry. Unlike the Lee government, which was the same political party, the Park government was seen as providing a weak response to climate change and global environmental issues as the host country of the GGGI and GCF.

4.2.2. Less Visible Smart Green City Initiatives Under the Park Government

At the global level, the Paris Agreement was unanimously passed at the 2015 United Nations Framework Convention on Climate Change Conference (COP21). With Korea ranked as the seventh largest producer of CO2 emissions in the world, the Park government submitted a plan to significantly reduce emissions. As noted, similar notions such as the ubiquitous eco-city (U-Eco City), carbon-neutral green cities, and low-carbon green cities had already emerged under the previous government. However, during the Park administration, the ITU and UNECE introduced the concept of smart sustainable cities at the global level, resulting in domestic research and the inclusion of projects aiming to solve problems with the living environment in existing smart city projects [74–76].

As such, interest in smart green cities grew during this period, with an increased preference for cities with more advanced smart technologies than U-city. Nevertheless, there were no government-level green city-related projects, and smart green city research had only been conducted at the R&D level. That said, projects that included green city elements were actively promoted as smart city projects at the time. For instance, in 2016, Pohang, a major steel manufacturing city, implemented the "Green Way" project, which combined an open smart city platform with eco-friendly green city factors [77,78].

Under the Park government, the concepts of the U-City and smart city coexisted. The Smart City project was managed by the Ministry of Land, Infrastructure, and Transport, which changed its name to its current name in 2013. These two grounds seem to have influenced how the next administration structured its Smart Green City project.

4.3. Critical Junctures

4.3.1. Pressure from the Global Community During the Moon Administration

Coming to power in 2017, the Moon administration sought to innovate the overall energy structure by emphasizing the safety of the energy mix, reducing nuclear power plants and fostering a new and renewable energy industry. In particular, the Moon administration encouraged the active participation of civil society in the government policymaking process, as well as the phasing out of nuclear power and the expansion of new and renewable energy. In this respect, the government planned to decommission nuclear power plants, reducing the number thereof from 24 in 2017 to 14 by 2038. Plans to build new power plants were canceled, extending the lifespan of existing nuclear power plants was banned, and the country's first nuclear power plant was shut down ahead of schedule [79]. However, despite these energy transition efforts, the Moon administration's interest in climate change—especially in terms of reducing greenhouse gas emissions—appears to have been lacking.

Meanwhile, in October 2018, the IPCC, a UN affiliate, released the Special Report on Global Warming of 1.5 °C [80]. Subsequently, in December 2018, the EC released "A Clean Planet for All", which declared that carbon neutrality should be reached by 2050. Announced in 2019, the European Green Deal Plan included a "strategy to achieve carbon neutrality by 2050", known as a new economic growth engine, climate protection, and industrial strategy. At the global level, the United States, Canada, Japan, and China followed the EU in declaring carbon neutrality goals for 2060.

4.3.2. COVID-19 and the Green New Deal Proposals Under the Moon Government

Under global pressure, the Moon administration faced two challenges. The first was the unexpected threat of COVID-19, which necessitated an economic stimulus package due to the economic downturn. The other was the 2015 Paris Agreement, which required the establishment of a Long-Term Low-Greenhouse Gas Emissions Development Strategy (LEDS) by 2020. In this respect, the Korean government had yet to prepare any such measures. Thus, when the Moon administration announced the Green New Deal in July 2020, its goal was to overcome both the economic crisis caused by COVID-19 and the emergent climate and ecological crises. The Green New Deal comprised 12 major tasks in four areas, with the goal of achieving a carbon-neutral economy from 2020 to 2025. The four areas were as follows: (1) the green transformation of cities, spaces, and living infrastructure; (2) the expansion of low-carbon distributed energy; (3) the development of a green industry innovation ecosystem; and (4) the establishment of a foundation for carbon neutrality (new establishment). As the department in charge of the Green New Deal, the Ministry of Environment announced the 2050 LEDS on 30 December 2020, which established Korea's 2050 vision and the basic direction for achieving climate neutrality by 2050 [79,81].

At the end of its term, the Moon administration officially announced the 2050 carbon-neutrality goal and sought to strengthen the institutional foundation necessary to move toward a carbon-neutral society. As part of this institutional foundation, the Presidential Carbon Neutrality and Green Growth Committee was launched in May 2021, followed by the enactment of the Framework Act on Carbon Neutrality and Green Growth in September 2021. Although the Moon government's institutionalization of the net-zero goal has been evaluated positively, Korea's greenhouse gas emissions increased by 4.2% in 2021 compared with the previous year, raising questions about the feasibility of achieving its neutrality goal. Moreover, a considerable number of NGO group members participated in government

ministries and commissions, eliciting constant objections regarding their qualifications and expertise [79].

4.3.3. Initiation of the Smart Green City Project for Carbon Neutral and Green Society Under the Moon Government

In order to overcome the limitations of the U-city, the Moon government revised the Smart City Act in 2017, announced a smart city promotion strategy in 2018, and established the 3rd Smart City Comprehensive Plan (2019–2023) in 2019. The government also passed the Act on the Promotion of Smart City Development and Industry in 2019, which defined "smart cities" as sustainable cities that improve urban competitiveness and quality of life based on ICT, linking smart cities to sustainable development. President Moon saw the Green New Deal, which included carbon neutrality and greenhouse gas reduction goals, as related to the environment, and designated the Ministry of Environment, rather than the Ministry of Land, Infrastructure, and Transport, as the ministry in charge of the project. As part of the Green New Deal, the Ministry of Environment initiated the Smart Green City project to secure a green urban ecosystem by 2020 [62]. Significantly, the Moon government transformed the Smart Green City project from a research project led by the Ministry of Land, Infrastructure, and Transport under the Park government into a project managed by the Ministry of Environment [82].

4.4. Reactive Sequence

4.4.1. Appointment of the Ministry of Environment to Lead the Project

In August 2020, the Ministry of Environment formed a support group for the Smart Green City public offering project and distributed project guidelines shortly thereafter [83]. The primary goal (vision) of the guidelines was to realize a sustainable future environmental city in which humans and nature coexist, as shown in Figure 2. The secondary goal was to promote locally led urban green transformation using green and smart technology and to improve the response to climate change, inclusiveness, and environmental quality. The project objectives emphasized the use of smart technology, inferring that smart technology was a means of achieving these goals. However, as Table 3 shows, the project's four major areas and basic directions do not clarify why and how smart technology should be used to transform cities into green cities. Although several countries have followed the development framework of Smart Sustainable Cities to solve various social and environmental problems, including carbon neutrality based on smart cities, Korea's Smart Green City project adopted a different approach [84].

4.4.2. Counter Reactions of Local Governments to the Project

A total of 100 local governments participated in the three-month project contest conducted by the Ministry of the Environment, with an average competition rate of 4 to 1. Among the 25 selected local governments, the general leading model received KRW 16.7 billion and the common model received KRW 10 billion in project expenses over a period of two years. Table 5 presents the final 25 Smart Green City project locations, the local governments of which signed an agreement with the Ministry of Environment in March 2021 [85]. As such, the local governments reacted positively to the Ministry of Environment's Smart Green City project. Distinctively, local governments that already had favorable conditions, such as the granting of bonus points, were more active in applying for budget support from the central government.

Table 5. The final list of local governments selected for the Smart Green City Project.

25 Locations	Bucheon city, Seongnam city, Ansung city, Anyang city, Yangju city, Pyeongtaek city, Hwasung city, local governments in Gangwon-do, Gangneung city, Jincheon county, Gongju city, Jangsu county, Jeonju city, Gangjin county, Suncheon city, Jangheung county, Haenam county, Sangju city, Pohang city, Gimhae city, Miryang city, Seo-gu of Incheon city, Dong-gu of Gwangju city, Saha-gu of Busan, Jeju city

Source: Ministry of Environment [85].

4.5. Outcome

However, despite spending 93% of the national treasury funds allocated to the Smart Green City project over the past two years, not a single one of the 25 selected local governments has achieved their goals. In view of these outcomes, the Ministry of Environment was criticized for not allocating enough time to conduct briefing sessions, contests, and the local government selection process, as well as failing to thoroughly review project feasibility or effectiveness. Indeed, during the project period, some local governments voluntarily abandoned the project and several others were explicitly ordered by the Ministry of Environment to halt the project [22–24].

Regarding the cause of these outcomes, it is worth noting that, among the variables that influenced Nakamura and Smallwood's policy implementation, the policy goals were unclear [86]. In other words, since the Ministry of Environment did not present specific measures other than the need to use smart green technology, it seems that the local governments selected for the project had difficulty starting the project immediately. Ultimately, due to the ambiguity of the goal and the lack of specific means to achieve it, it would have been challenging to guarantee the sustainability of the Smart Green City project.

4.6. Summary of Findings

Table 6 presents detailed results. Number (1) to number (3) are the results of the analysis elements within the critical juncture framework. Number (4) and (5) are explanations of the results of preceding numbers (1) to (3).

Table 6. Summary of Smart Green City Project mechanisms.

No.	Elements	Lee Government	Park Government	Moon Government
(1)	Institutional context: Conceptualization of the Smart Green City	Solely use of U-city	Invisibly mixed use of Smart City, Green City, and Smart Sustainable City	Separate use of Smart City and Smart Green City
(2)	Key actors	Presidential Green Growth Committee/Ministry of Land, Transport and Maritime Affairs	Prime Minister's Green Growth Committee/Ministry of Land, Infrastructure and Transport	Carbon Neutrality Commission/Ministry of Environment
(3)	Events	Low Carbon, Green Growth strategy/Green New Deal	Creative Economy strategy/Low Carbon, Green Growth strategy	Carbon Neutrality and Green Growth strategy/Green New Deal
(4)	Type of path dependence	Self-reinforcing sequences		Reactive sequences
(5)	Features and variables of policy change related to the Smart Green City project	Policy initiation/Antecedent condition	Maintaining the existing policy/Permissive condition	Reproducing the existing policies/Critical juncture

(1) Institutional context (process of conceptual change in the Smart Green City): In this regard, this study identified the institutional context that led to conceptual changes from a U-city to a smart city and from a smart city and a green city to a smart green city. Unlike previous governments, the Moon administration appears to have focused on pursuing smart city and smart green city policies separately.

(2) Key actors: Under the Lee government, key players in related policies included the President's Green Growth Committee and Ministry of Land, Infrastructure, Transport, and Maritime Affairs. Under the Park government, the Prime Minister's Green Growth Committee and the Ministry of Land, Infrastructure, and Transport were the responsible ministries. However, under the Moon government, the Carbon Neutrality Committee and Ministry of Environment were key policy actors. A distinctive feature was that the chairmen and ministers of these institutions were all from NGOs.

(3) Events: The Lee government took the lead in responding to climate change by promoting a low-carbon green growth strategy and the Green New Deal plan. Although the Park government established a new energy industry revival strategy called the "creative economy", it attempted to maintain the low-carbon green growth strategy promoted by

the Lee administration. Meanwhile, the Moon government appears to have copied many of the strategic names and concepts used by the Lee government [76,77].

The Lee and Park governments failed to fulfill their promises to the international community, including those related to carbon emission reduction, over their collective ten years in office, while other countries did so to a high level. Facing a sense of crisis and international pressure, the Moon government had no choice but to make strong appeals confirming their commitment to environmental redress, such as suggesting new goals and declaring definitive plans. However, as a change in regime approached, without time to introduce a new institution, the Moon government appears to have chosen a path dependent on existing institutions.

(4) Type of path dependence: As the Park government maintained the Lee government's U-city and green growth policies, its path dependence on existing government policy appears to have been a self-reinforcing sequence type. In contrast, the Moon government appears to have a reactive sequence type, insofar as it attempted to establish a new path by combining events through the Smart Green City project while reproducing the smart city and green city strategies of previous administrations.

(5) Features and variables of policy change related to the Smart Green City project: The Lee government's low-carbon, green growth strategy and Green New Deal were unique Korean policy attempts. This does not mean that similar laws and policies did not exist. As such, the main feature of the Lee government was the initiation of a policy that was an antecedent condition contributing to the shift toward smart green city orientation, rather than policy innovation. The Park government maintained most of the policies of the Lee government. Although no government-level projects were promoted under the Park administration, research on smart green cities was conducted. This seems to have become a permissive condition for the Moon government to launch the Smart Green City project.

The Moon government attempted to differentiate itself from existing government policies by designating the Ministry of Environment as the project enabler. However, local governments that implemented the project did not achieve the results they expected because the Ministry of Environment failed to present clear goals and means for the projects. These facts, under the Moon government, suggest that the Smart Green City project might have been promoted based on political judgment within the framework of the Korean Green New Deal's grand initiative, rather than being purely intended to create a carbon-neutral city to resolve environmental issues [21,87].

The policy change mechanism related to the Smart Green City project was analyzed as follows. Korea's Smart Green City project was conceptually connected to the U-city, smart city and green city in an institutional context. The low-carbon, green growth policy and smart city policy established by the Lee government were weakly maintained by the Park government. The Moon government created the Smart Green City project by combining the policies and programs of previous governments. The Moon government returned to the Lee government's Green New Deal to find a breakthrough during a critical juncture, namely, the intersection of international pressure to reduce greenhouse gases and the economic recession crisis caused by COVID-19, with the Smart Green City project used as a policy means to this end. Therefore, this study argues that the Smart Green City project is the outcome of the Moon government reproducing a significant portion of existing government policies for political intention. Korea's Smart Green City project seems to have emerged as a new pillar of the Green New Deal policy that deals with carbon neutrality, but it has shown limitations in finding a new path due to its path dependency on existing policies. Nevertheless, the Moon government has attempted to differentiate itself from existing government policies by designating the Ministry of Environment, which is unrelated to the smart technology that is the means of this project, as the ministry in charge. They might have judged that Environment Ministers from civil society can most quickly and faithfully implement the Green New Deal plan.

These results imply that governments facing critical junctures such as exogenous and endogenous crises related to the environment and economy may first consider the relevant

policies of previous governments to overcome the crisis and seek to differentiate their policies from previous government policies based on political judgment.

5. Discussion

This study aimed to identify the mechanism of policy change that led the Korean government to fully pursue the Smart Green City project using a critical juncture approach and to derive useful implications for future policy choices.

This case illustrates that when a government facing multiple crises related to the environment and economy makes hasty political policy decisions at a critical juncture without considering sustainability, it is likely to repeat the policy direction or institutional path of the previous government. Moreover, it highlights that policy decisions aimed at differentiation in these situations can set one down an irreversibly incorrect path. The implications through the case analysis are as follows. During a critical juncture, the government's response to multiple crises of exogenous and endogenous changes and the president's will to break away from the reproduction of existing government policies can be the driving force behind large-scale national environmental projects. However, rushing a project in an urgent situation can lead to the reproduction of existing policies and the achievement of unexpected results. In addition, it argues that attempts to differentiate policies that already show path-dependent characteristics with respect to past policies can rather act as a constraint that hinders project implementation. Thus, caution is required in this regard.

The Korea's Smart Green City project was actually halted after the Yoon administration took office. However, though all 25 project locations had a performance achievement rate of zero by the end of the project period in 2022, the current government has conditionally extended the project termination date due to the sunk cost issue, and it is thus being continued. This study treated Korea's Smart Green City project as a single case. Follow-up studies could perform comparative research for countries that have already had similar experiences. It might be also pointed out that there were limitations regarding the accessibility of official work-related documents and web documents because the research subject was a project that was already considered to have been discontinued.

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References

1. Seneviratne, S.I.; Nicholls, N.; Easterling, D.; Goodess, C.; Kanae, S.; Kossin, J.; Luo, Y.; Marengo, J.; McInnes, K.; Rahimi, M.; et al. Changes in climate extremes and their impacts on the natural physical environment. In *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*; A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, (IPCC); Field, C.B., Barros, V., Stocker, T.F., Dahe, Q., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2012; pp. 109–230. [CrossRef]
2. Ministry of Environment. White Paper of Environment. 2022. Available online: https://www.kepaedu.or.kr/board/data/view.do?no=473&pageNo=1&schArea=&schType=all&schString (accessed on 10 May 2024).
3. The European Union. Carbon Border Adjustment Mechanism. Available online: https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en (accessed on 10 May 2024).
4. The White House. Inflation Reduction Act Guidebook. Available online: https://www.whitehouse.gov/cleanenergy/inflation-reduction-act-guidebook/ (accessed on 15 June 2024).
5. KISTEP (Korea Institute of Science & Technology Evaluation and Planning). Carbon Neutrality Trends and R&D Promotion Strategies in Major Countries. Available online: https://www.kistep.re.kr/gpsIssueView.es?mid=a30101000000&list_no=49118 (accessed on 10 February 2024).
6. International Energy Agency (IEA). World Energy Outlook 2023. Available online: https://www.iea.org/reports/world-energy-outlook-2023 (accessed on 14 May 2024).
7. Iyke, B.N. Climate change, energy security risk, and clean energy investment. *Energy Econ.* **2024**, *129*, 107225. [CrossRef]
8. Arndt, C. Climate change vs. energy security? The conditional support for energy sources among Western Europeans. *Energy Policy* **2023**, *174*, 113471. [CrossRef]

9. Ministry of Environment. White Paper of Environment. 2020. Available online: https://library.me.go.kr/#/search/detail/5880602?offset=1 (accessed on 10 May 2024).
10. Kamal-Chaoui, L.; Grazi, F.; Grazi, F.; Plouin, M. *The Implementation of the Korean Green Growth Strategy in Urban Areas. OECD Regional Development Working Papers 2011/02*; OECD Publishing: Paris, France, 2011. [CrossRef]
11. Climate Change Performance Index. Available online: https://ccpi.org/ranking/ (accessed on 2 February 2024).
12. Korea JoongAng Daily. Don't Be a Climate Villain. Available online: https://koreajoongangdaily.joins.com/2020/05/18/columns/villain-climate-green-new/20200518211100151.html (accessed on 20 January 2024).
13. Climate Home News. South Korea Leads List of 2016 Climate Villains. Available online: https://www.climatechangenews.com/2016/11/04/south_korea_climate_villains/ (accessed on 2 February 2024).
14. The Korea Times. Long Way to Become Climate Leader. Available online: https://www.koreatimes.co.kr/www/opinion/2024/05/638_309344.html (accessed on 7 February 2024).
15. Ministry of Economy and Finance. Korea's Green New Deal: Towards a Low-carbon Society. Available online: https://www.greenclimate.fund/sites/default/files/event/koreas-green-new-deal-moef-international-conference-green-new-deal.pdf (accessed on 22 January 2024).
16. Republic of Korea's Policy Briefing. Korean New Deal. Available online: https://www.korea.kr/briefing/policyBriefingView.do?newsId=148874860#policyBriefing (accessed on 3 February 2024).
17. Korean Broadcasting System News. Ministry of Environment Begins Public Contest to Select Target Areas for Smart Green City Project. Available online: https://news.kbs.co.kr/news/pc/view/view.do?ncd=4534798 (accessed on 2 March 2024).
18. Smart City Korea. Ministry of Environment, Smart Green City Project Target Area Competition. Available online: https://smartcity.go.kr/en/2020/09/08/%ED%99%98%EA%B2%BD%EB%B6%80-%EC%8A%A4%EB%A7%88%ED%8A%B8-%EA%B7%B8%EB%A6%B0%EB%8F%84%EC%8B%9C-%EC%82%AC%EC%97%85%EB%8C%80%EC%83%81-%EC%A7%80%EC%97%AD-%EA%B3%B5%EB%AA%A8/ (accessed on 23 March 2024).
19. UN. From Green Economies to Green Societies. Available online: https://sdgs.un.org/publications/green-economies-green-societies-17502 (accessed on 11 February 2024).
20. UNECE. Smart Sustainable Cities. Available online: https://unece.org/search_unece_content?keyword=u4ssc (accessed on 11 February 2024).
21. Korea Legislation Research Institute. *What Is the Green New Deal for?* Legal Studies; Korea Legislation Research Institute: Sejong, Republic of Korea, 2020; p. 68.
22. Ministry of Environment. Smart Green City, Created by the Ministry of Environment and the Region Together. Press Release. Available online: https://www.korea.kr/briefing/pressReleaseView.do?newsId=156409921 (accessed on 2 February 2024).
23. The Chosun Daily. 158 Billion Won Spent on "Smart Green City" Achievement Rate 0%. Available online: https://www.chosun.com/national/transport-environment/2023/02/03/T23NDQ3EANATXC5OKXDQOGSTZU/ (accessed on 27 February 2024).
24. Korea Construction Newspaper. Smart Green City, Will It End as a 'Fool's Gold'? Available online: http://www.conslove.co.kr/news/articleView.html?idxno=76778 (accessed on 3 March 2024).
25. Energy Newspaper. Will the Problematic 'Smart Green City' Be Achieved This Year? Available online: https://www.energy-news.co.kr/news/articleView.html?idxno=86305 (accessed on 3 March 2024).
26. OhmyNews. Korean New Deal? Updating the Lee Myung-Bak and Park Geun-Hye Policies with New Names. Available online: https://m.ohmynews.com/NWS_Web/Mobile/amp.aspx?CNTN_CD=A0002660263 (accessed on 3 March 2024).
27. Mahoney, J. Path dependence in historical sociology. *Theory Soc.* **2000**, *29*, 507–548. [CrossRef]
28. Sorensen, A. Taking critical junctures seriously: Theory and method for causal analysis of rapid institutional change. *Plan. Perspect.* **2023**, *38*, 929–947. [CrossRef]
29. Mahoney, J.; Thelen, K.A. *Explaining Institutional Change: Ambiguity, Agency, and Power*; Cambridge University Press: Cambridge, UK, 2010.
30. Collier, D.; Munck, G. Building blocks and methodological challenges: A framework for studying critical junctures. *Qual. Multi-Method Res.* **2017**, *15*, 2–9.
31. Evans, P.; Rueschmeyer, D.; Skocpol, T. *(Eds). Bringing the State Back in*; Cambridge University Press: Cambridge, UK, 1985.
32. Hall, P.A. *Governing the Economy: The Politics of State Intervention in Britain and France*; Oxford University Press: Oxford, UK; New York, NY, USA, 1986.
33. Peters, G.B.; Pierre, J.; King, D.S. The politics of path dependency: Political conflict in historical institutionalism. *J. Politics* **2005**, *67*, 1275–1300. [CrossRef]
34. Hall, P.A.; Taylor, R.C. Political science and the three new institutionalism. *Political Stud.* **1996**, *44*, 936–957. [CrossRef]
35. Pierson, P. Increasing returns, path dependence, and the study of politics. *Am. Political Sci. Rev.* **2000**, *94*, 251–267. [CrossRef]
36. Ha, Y.S. *Institutional Analysis: Theories and Issues*; Dasan Publishing: Seoul, Republic of Korea, 2004.
37. Pierson, P.A. *Politics in Time: History, Institutions, and Social Analysis*; Princeton University Press: Princeton, NJ, USA, 2004.
38. Immergut, E.M. The theoretical core of the new institutionalism. *Politics Soc.* **1998**, *26*, 5–34. [CrossRef]
39. Clemens, E.S.; Cook, J.M. Politics and institutionalism: Explaining durability and change. *Annu. Rev. Sociol.* **1999**, *25*, 441–466. [CrossRef]
40. Thelen, K. Historical institutionalism in comparative politics. *Annu. Rev. Political Sci.* **1999**, *2*, 369–404. [CrossRef]
41. Campbell, J.L. *Globalization and Institutional Change*; Princeton University Press: Princeton, NJ, USA, 2004.

42. Bennett, A.; Elman, C. Complex causal relations and case study methods: The example of path dependence. *Political Anal.* **2006**, *14*, 205–267. [CrossRef]
43. Roberts, K.M. Chapter 9 Aftermath: Reactive sequences and institutional legacies. In *Changing Course in Latin America: Party Systems in the Neoliberal Era*; Cambridge University Press: Cambridge, UK, 2015; pp. 229–270. Available online: https://www.cambridge.org/core/books/abs/changing-course-in-latin-america/aftermath-reactive-sequences-and-institutional-legacies/13EAB4849F211502CAE40B36C6357649 (accessed on 20 February 2024).
44. Thelen, K. How institutions evolve: Insights from comparative historical analysis. In *Comparative Historical Analysis in the Social Science*; Mahoney, J., Rueschemeyer, D., Eds.; Cambridge University Press: New York, NY, USA, 2003.
45. Collier, D.; Munck, G. *Critical Junctures and Historical Legacies: Insights and Methods for Comparative Social Science*; Rowman & Littlefield: Lanham, MD, USA, 2022.
46. Collier, R.B.; Collier, D. *Shaping the Political Arena: Critical Junctures, the Labor Movement, and the Regime Dynamics in Latin America*; Princeton University Press: Princeton, NJ, USA, 1991; Chapter 1.
47. Capoccia, G. Critical junctures and institutional change. In *Advances in Comparative Historical Analysis*; Mahoney, J., Thelen, K., Eds.; Cambridge University Press: Cambridge, UK, 2015; pp. 147–179.
48. Soifer, H. The causal logic of critical junctures. *Comp. Political Stud.* **2012**, *45*, 1572–1597. [CrossRef]
49. Smart City Korea. Available online: https://smartcity.go.kr/en/%EC%86%8C%EA%B0%9C/ (accessed on 7 April 2024).
50. Lee, D.C.; Sohn, S.H.; Kim, D.N. Establishing the Concept of Green City and its Approach into Practice. *Urban Des.* **2013**, *14*, 121–137.
51. Breuste, J. The Green City: General concept. In *Making Green Cities—Concepts, Challenges and Practice*; Springer: Berlin/Heidelberg, Germany, 2020; pp. 1–15.
52. Lee, S.H.; Han, H.; Yigitcanlar, T. Towards ubiquitous city: Concept, planning, and experiences in the Republic of Korea. In *Knowledge-Based Urban Development: Planning and Applications in the Information Era*; IGI Global: Hershey, PA, USA, 2008; pp. 148–169.
53. Ministry of Environment. *Guidelines for Smart Green City Project*; Public Offering: Sejong, Republic of Korea, 2020.
54. Smart City Korea. Publication of 2022 Urban Planning Statistics. Available online: https://smartcity.go.kr/en/2023/07/18/2022%EB%85%84-%EB%8F%84%EC%8B%9C%EA%B3%84%ED%9A%8D%ED%98%84%ED%99%A9-%ED%86%B5%EA%B3%84-%EA%B3%B5%ED%91%9C/ (accessed on 3 April 2024).
55. United Nations. Global Sustainable Development Report (GSDR) 2019. Available online: https://sdgs.un.org/gsdr/gsdr2019 (accessed on 15 March 2024).
56. CCPI. Republic of Korea. Available online: https://ccpi.org/country/kor/ (accessed on 17 June 2024).
57. Climate Action Tracker. Available online: https://climateactiontracker.org/countries/south-korea/ (accessed on 17 June 2024).
58. Republic of Korea's Policy Briefing. 25 Smart Green Cities to Be Create, 290 Billion Won Invested over Two Years. Available online: https://www.korea.kr/news/policyNewsView.do?newsId=148877202 (accessed on 10 March 2024).
59. National Archives of Korea. Low Carbon Green Growth. Available online: https://www.archives.go.kr/next/newsearch/listSubjectDescription.do?id=009245&sitePage= (accessed on 3 March 2024).
60. Moonwha Newspaper. Let's Start the Era of Low-Carbon Green Growth. Available online: https://www.munhwa.com/news/view.html?no=2008081601110123029001O (accessed on 17 March 2024).
61. Maeil Business Newspaper. We Need to Save Both the Environment and the Economy with the Green New Deal. Available online: https://www.mk.co.kr/news/special-edition/4657026 (accessed on 9 March 2024).
62. Food and Agriculture Organization of United Nations. Framework Act on Low Carbon, Green Growth. FAOLEX Database. Available online: https://www.fao.org/faolex/results/details/en/c/LEX-FAOC100522/ (accessed on 10 March 2024).
63. The Framework Act on Low Carbon, Green Growth. Available online: https://elaw.klri.re.kr/eng_mobile/viewer.do?hseq=49999&type=part&key=39https://elaw.klri.re.kr/eng_mobile/viewer.do?hseq=49999&type=part&key=39 (accessed on 10 February 2024).
64. Global Green Growth Institute. Available online: https://un-rok.org/about-un/offices/gggi/ (accessed on 17 March 2024).
65. Dong-A Ilbo, M.B. Korea Will Strive to Make the Green Triangle Work. Available online: https://www.donga.com/news/Politics/article/all/20120622/47201589/9 (accessed on 12 May 2024).
66. Green Growth. GGGI Officially Launched, Leading the Green Revolution. Available online: http://17greengrowth.pa.go.kr/?p=57242 (accessed on 20 March 2024).
67. Republic of Korea Policy Briefing. The Lee Myung-Bak Administration's Basic Plan for National Informatization Is Confirmed. Available online: https://www.korea.kr/briefing/pressReleaseView.do?newsId=155326317#pressRelease (accessed on 21 March 2024).
68. Ministry of Land; Transport and Maritime Affairs; Five Other Ministries. *Green City and Building Revitalization Plan*; The 6th Green Growth Committee: Sejong, Republic of Korea, 2009.
69. Choi, H.S.; Song, S.K. Direction for a transition toward smart sustainable cities based on the diagnosis of smart city plans. *Smart Cities* **2023**, *6*, 156–178. [CrossRef]
70. Kim, Y.M.; Lee, J.H. A study on the planning indicator for carbon neutral green city. *Korea Inst. Ecol. Archit. Environ.* **2013**, *13*, 131–139. [CrossRef]

71. Kyunghyang Shinmun. The Park Administration, Erases 'MB traces' and Ministry title 'Green' Disappears. Available online: https://www.khan.co.kr/politics/president/article/201303262215085 (accessed on 10 May 2024).
72. The Korea Herald. Park Ditches 'Green Growth' in Environmental Policy Shift. Available online: https://www.koreaherald.com/view.php?ud=20130328000986 (accessed on 20 April 2024).
73. Kim, Y.R.; New Industries in Energy Sector: Strategy for Extending Results. Korea Institute for Industrial Economics and Technology, Industrial Economy Analysis. Available online: https://www.kiet.re.kr/searchAll?collection=ALL&category=kiet_research&query=%EC%97%90%EB%84%88%EC%A7%80%20%EB%B6%84%EC%95%BC%EC%9D%98%20%EC%83%88%EB%A1%9C%EC%9A%B4%20%EC%82%B0%EC%97%85&sort=RANK&reQuery=1&realQuery=%EA%B9%80%EC%9A%A9%EB%9E%98&listCount=10&startCount=0 (accessed on 3 May 2024).
74. Korea Research Institute for Human Settlements. Successful Realization of a Smart Green City. *Plan. Policy*. 2016. Available online: https://library.krihs.re.kr/library/10110/contents/5869852?checkinId=2147733&articleId=1405797 (accessed on 3 May 2024).
75. Korea Development Institute. Korean Cities, Need a Major Transformation into 'Smart Green Cities'. *Narakyungje*. 2016. Available online: https://eiec.kdi.re.kr/publish/naraView.do?fcode=00002000040000100001&cidx=10343&sel_year=2016&sel_month=01 (accessed on 25 April 2024).
76. Ryu, S.Y.; Lee, J.W. A governance approach for the Sustainable Smart City. *J. Korean Urban Manag. Assoc.* **2019**, *32*, 81–96. [CrossRef]
77. National Balanced Development Information System. Pohang Railroad Forest Completed, Greenway Unfolded in the City Center. Available online: https://www.nabis.go.kr/outstandRegionDetailView.do?menucd=190&outstandNo=626&appfileNo=13741 (accessed on 4 May 2024).
78. Korea Research Institute for Human Settlements. A Study on Strategic Response to Smart City Types. KRIHS, Research Report. 2019, pp. 13–18. Available online: https://library.krihs.re.kr/library/10180/contents/6166524 (accessed on 6 June 2024).
79. Chung, S.Y.; Lee, G.E. South Korea's Climate Change Policy: Achievements and Tasks Ahead. The Korea Economic Institute of America (KEI). 2022. Available online: https://keia.org/publication/south-koreas-climate-change-policy-achievements-and-tasks-ahead/ (accessed on 20 April 2024).
80. Intergovernmental Panel on Climate Change (IPCC). Summary for Urban Policymakers—What the IPCC Special Report on 1.5C Means for Cities. Available online: https://www.ipcc.ch/site/assets/uploads/sites/2/2018/12/SPM-for-cities.pdf (accessed on 22 April 2024).
81. Cho, B.K.; Chung, J.B.; Song, C.K. National Climate Change Governance and Lock-in: Insights from Korea's Conservative and Liberal Governments' Committees. *Energy Strategy Rev.* **2023**, *50*, 101238. [CrossRef]
82. Choi, H.S.; Park, C.S.; Shin, D.W. Transition Strategy to a Smart Sustainable City. Korea Environment Institute: Seoul, Republic of Korea, 2021; Volume 9.
83. The Constimes. Ministry of Environment Forms Smart Green City Promotion Project Support Group. Available online: https://www.constimes.co.kr/news/articleView.html?idxno=215740 (accessed on 24 April 2024).
84. UNECE. Smart Sustainable Cities. Available online: https://unece.org/housing/smart-sustainable-cities (accessed on 2 May 2024).
85. Ministry of Environment. *Declaration of Vision to Lead Korea to Carbon Neutrality as a Smart Green City*; Press Release; Ministry of Environment: Seoul, Republic of Korea, 2021.
86. Nakamura, R.T.; Smallwood, F. *The Politics of Policy Implementation*; St. Martin's Press: New York, NY, USA, 1980.
87. NEWSTOF. Moon Jae-in's 'Green New Deal' Wandering Between Lee Myung-bak and the Justice Party. Available online: https://www.newstof.com/news/articleView.html?idxno=10819 (accessed on 2 May 2024).

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Research on the Impact Mechanism of ETS on Green Innovation in China's High-Carbon Industries: A Perspective of Enterprise Heterogeneity

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Abstract: Green technology innovation is an important driving force for low-carbon development of enterprises. As a market-based environmental policy to promote greenhouse gas emission reduction, whether carbon emission trading scheme (ETS) can encourage enterprises to carry out green technology innovation under the background of "dual carbon" goal deserves further research. Taking Chinese A-share listed enterprises in the five major sectors as samples, this study constructed a modified Difference-in-Differences (DID) model to test the causal effect of ETS on green innovation in high-carbon industries. Three significant results can be summarized from the empirical study. Firstly, the ETS has a significant promoting effect on green innovation of high-carbon enterprises. And it can effectively promote high-carbon enterprises to achieve an average of a 13.24–19.56% increase in low-carbon innovation capabilities. Secondly, enterprises with different characteristics have heterogeneity in the impact of ETS implementation on green innovation. Secondly, the implementation of ETS exerts heterogeneous effects on green technology innovation across enterprises that possess diverse characteristics. Enterprises with a large capital scale (low equity concentration) have a more significant promoting effect than those with a small capital scale (high equity concentration). Thirdly, the green innovation effect of ETS exhibits significant heterogeneity across different types of industries. In the mining, manufacturing, and construction sectors, the ETS has effectively stimulated green innovation to a certain extent. There has been no significant change in green innovation in the sector of electricity, heat, gas, and water production and supply. In particular, after the implementation of the ETS, green innovation has actually been weakened in the transportation sector. As such, for policy makers, differentiated ETS policies should be implemented based on the actual situation of different industries and types of carbon-emitting enterprises.

Keywords: ETS; green innovation; DID; heterogeneity; high-carbon enterprises

1. Introduction

As the world's largest greenhouse gas emitter and a responsible major country, after the proposal of the dual carbon target (carbon peak by 2030 and carbon neutral by 2060), various industries have successively introduced a series of environmental laws, policies, regulations and other measures to implement this commitment [1]. Of which, the Emission Trading Scheme (ETS) has long been regarded as the most effective tool for controlling greenhouse gas emissions and achieving carbon neutrality. Basically, ETS is a way of clearly defining the subject of emission rights, marketizing carbon emission rights, and controlling total carbon emissions within an appropriate range [2]. Therefore, the ETS is also known as the cap and trade policy.

Compared to developed countries such as the European Union and the United States, China's implementation of the ETS policy was relatively late. In October 2011, the National

Development and Reform Commission (NDRC) approved seven regions to launch a pilot carbon emissions trading scheme. In 2013, Shenzhen took the first step to implement the pilot scheme, followed by the other six regions. In 2016, Fujian province joined the carbon trading pilot scheme. Thereafter, in 2017, the NDRC promulgated the National Carbon Emissions Trading Market Construction Plan (Power Generation Sector), which marked the official launch of the national carbon emissions trading market. Currently, the carbon trading market in China has more than 2000 key emission units in the power generation industry, with carbon emissions exceeding 4 billion tons, surpassing the EU ETS and becoming the world's largest emissions trading scheme [3]. The ETS has made initial progress in energy conservation and emission reduction in recent years, providing valuable experience for the large-scale promotion of the policy across the country [4].

ETS policies mainly generate economic incentives through market mechanisms, which in turn stimulate enterprises to adopt innovative technologies and methods to achieve carbon emissions reduction. However, factors such as emission costs can also impose certain constraints on the implementation of environmental regulatory policies. Whether the implementation of ETS policies can promote economic growth while protecting the environment has become a hot research topic. The existing research on the effectiveness of ETS policies mainly focuses on the evaluation of environmental-economic effects, and there is relatively few in-depth analysis of the impact mechanism behind this effect. This leads to three issues that need further research: (1) Is the implementation of ETS policies effective in reducing carbon emissions and improving corporate green innovation capabilities? (2) What are the specific impact pathways of ETS policies? (3) Is there significant heterogeneity in the implementation effect of ETS among different types of emission enterprises? Taking Chinese A-share listed companies in the five major sectors from 2010 to 2019 as samples, this study constructed a multi-period Propensity Score Matching Difference-in-Differences (PSM-DID) model to empirically test the environmental and economic effects of ETS policy, and further explore the impact path and heterogeneity of this policy on the green innovation effect of high car-bon enterprises.

The possible marginal contribution of this study lies in the following three aspects: (1) in terms of research content, the evidence for the validity of the Porter hypothesis in China's environmental regulation reform mostly remains at the macro level, and the conclusions have not reached a consensus. This study delves into the micro-enterprise level, focusing on the impact of ETS on green innovation of enterprises, confirming that China's market-oriented environmental regulation reform can achieve the Porter hypothesis. (2) In terms of research methodology, this study constructs a multi-period PSM-DID method, which can effectively weaken the endogeneity of the sample selection. Thus, a meticulous and scientifically sound evaluation of the influence of ETS net policies on green technology innovation in enterprises can be conducted. In addition, this study innovatively starts from various dimensions such as firm size, equity concentration, and industry categories to further examine the heterogeneity of the impact of ETS. (3) In reality, the government has proposed the construction of a nationwide carbon emissions trading market. This study will help identify problems in a timely manner, formulate corresponding policy measures, and better promote the continued implementation of the policy nationwide.

2. Literature Review

Global warming caused by the increase in carbon dioxide (CO_2) concentrations has led to serious impacts on the human living environment, such as frequent extreme weather and air pollution [5]. According to the International Energy Agency (IEA), by the end of 2022, the CO_2 emissions generated by fossil energy consumption were 36.8 billion tons, setting a new historical high [6]. To address the negative externalities of carbon emissions, environmental regulations have been widely applied. There has been a heated debate over the impact of existing environmental regulations on their effectiveness. Neoclassical economics believes that environmental regulations can lead to additional costs for businesses and have a negative impact on the country's economic growth. Meanwhile, the Porter

hypothesis suggests that reasonable and strict environmental regulations are conducive to incentivizing companies to engage in innovative activities, reducing their additional environmental costs, and achieving a win–win situation for both the environment and the economy.

According to the types of environmental regulations, existing studies on the relationship between environmental regulation and corporate green technology innovation can be divided into three categories. One is administrative command based environmental regulation, which mainly achieves established environmental goals through mandatory intervention. The second type is the market-oriented environmental regulation, which mainly emphasizes the role of market allocation of resources to achieve environmental goals. The third type is the emerging voluntary environmental regulation. Environmental issues are negative externalities caused by market participants. To solve environmental problems, it is necessary for participants who cause negative externalities to make compensation, and this compensation can precisely compensate for the negative behavior they have caused to society. Relatively, market-based environmental regulation is more flexible than administrative command based environmental regulations, and more restrictive than voluntary environmental regulations. Market-based environmental regulation can better leverage the resource allocation function of the market.

As one of the representative policies of market-oriented environmental regulation, ETS policy has gradually become one of the effective policies for controlling environmental pollution. The core of ETS policy is the allocation of enterprise emission quotas based on total quantity control. Emission rights can be freely traded in the market, and high emission enterprises can purchase excess emissions and sell them to increase their profits, thereby utilizing market forces to achieve effective resource allocation. On the one hand, by setting emission quotas for enterprises, ETS policies can achieve the effect of carbon reduction. Sun et al. [6] studied the impact of ETS on carbon intensity and its mechanism, and found that the policy reduces carbon intensity by adjusting industrial structure, while energy structure and energy intensity have not played a role. In addition, in the research by Fang et al. [7], China's ETS was simulated through a non-linear programming. They found that implementing a carbon emissions trading system is economically meaningful in achieving the dual goals, as it will reduce China's emission reduction costs by 61.41–80.33% from 2016 to 2030.

On the other hand, the effective implementation of ETS policies is not only about reducing emissions, but also about promoting green economic development. Wu and Zhu [8] reviewed the impact research of ETS from four aspects: emissions reduction, economic performance, competitiveness, and innovation. The main goal of ETS is to reduce emissions, while the other long-term goal is to promote innovation. In order to keep their carbon emissions within the stipulated cap, enterprises have to take effective measures to cope with this policy [9]. Most scholars, after model derivation or empirical analysis, believe that ETS has a positive promotion effect on green technology innovation [10–12]. Representative studies included Liu and Sun [13], which empirically found that China's ETS pilot can significantly promote the increase in green technology innovation, and the effect of China's ETS pilot on green technology innovation will gradually increase over time. However, a few scholars have found that ETS policies experienced a crowding-out effect on innovation and confirmed this phenomenon through mechanism analysis.

Overview of existing studies, scholars have achieved fruitful results. Nevertheless, no consensus has been reached on the impact of any environmental regulation on innovation. Further analysis can still be expanded in the following two aspects. Firstly, most studies have examined the green innovation effects of environmental policy implementation from the perspective of policy makers at the macro level, but lacked research on how ETS affect enterprises' green innovation at the micro-perspective. Overall CO_2 emissions can only be reduced radically by finding ways to enable individual micro-enterprises to develop green innovations on their own. Secondly, it is particularly important to clarify how ETS affect the direction of technological change in enterprises. Instead of a one-size-fits-all emissions

control policy, policy makers should propose feasible green innovation solutions suitable for different types of enterprises to cope with environmental regulation policies. Therefore, this study explores the impact of China's carbon emissions trading pilot policies on green innovation in high-carbon enterprises. This will help to discover the practical strategies that different emission control companies tend to adopt when responding to policies, and explore the real motivations behind the increase in green innovation in enterprises.

3. Theoretical Analysis and Research Hypotheses

3.1. The Impact of ETS on Green Innovation

The impact of environmental regulation on green innovation has been fully investigated in the existing literature. For enterprises, the enhancement of green technology innovation comes from two aspects: firstly, enterprises add additional funds, fixed assets investment and human resources on the basis of existing innovation activities to specifically support green technology innovation, so that existing innovation activities have a "leverage effect" on green innovation [14]; Secondly, enterprises will optimize the allocation of internal resources, using resources originally intended for other innovative or business activities for green technology innovation [15]. This not only promotes green technology innovation, but also has a certain "crowding out effect" on other innovative behaviors of the enterprise.

As a market-oriented environmental regulation measure, ETS policy may affect the choice of corporate behavior in the following three ways: firstly, market participants will see carbon emissions trading policy as a signal for the government to strengthen environmental regulation, and enterprises will gradually realize their emission problems in operation, thereby strengthening technological innovation in emission control [16]. Secondly, the introduction of carbon emissions trading policies has reduced the policy uncertainty for enterprises to invest in emission control [17]. Various continuous environmental regulations have made enterprises realize the necessity of emission control and continuously eliminate their concerns about low or even no returns on investing funds in the emission control field. This can motivate enterprises to make long-term investments, which plays a promoting role in innovative behavior. Finally, environmental regulations are widely implemented for enterprises, which can create a fair competitive market environment [18]. Moreover, the carbon emissions trading mechanism relies on the market, and the allocation of resources is more flexible and effective, which is undoubtedly more conducive to guiding enterprises towards green technology innovation choices. In general, ETS can promote corporate green technology innovation through a "leverage + crowding out" approach.

This study focuses on the impact of carbon ETS on green innovation in high-carbon enterprises to confirm whether the innovation compensation effect can offset the innovation crowding out effect caused by compliance costs. In other words, aiming at profit maximization, enterprises may adjust their practices in the face of environmental regulations to meet emission standards at lower costs. Thus, environmental regulation may stimulate innovation in a particular area. As Levinson and Taylor [19] pointed out, high-carbon enterprises invest more factors in technological research and development after the government adopts environmental regulation. Responding to environmental regulations through a green innovation approach requires that enterprises have sufficient funds to invest in R&D so that they can improve the energy efficiency of their processes and production equipment, or else they must pay the prescribed costs of non-compliance [20,21]. As a market-based environmental regulatory tool that stimulates the advanced and pushes the backward, the carbon ETS is equally applicable, leading to the following hypothesis:

H1. The carbon ETS can effectively promote high-carbon enterprises to promote green innovation.

3.2. Heterogeneity of the Impact

Generally, it is recognized that the higher the quality of a firm's innovation, the more competitive advantage it has in the marketplace [22]. However, considering that it takes time for enterprises to adjust their innovation strategies, enterprises can carry out appropriate technological application innovation within the existing technological framework in the short term. This can not only avoid the uncertainty risk brought by original technological innovation, but also enable enterprises to enjoy the innovation compensation effect brought by application innovation more quickly [23]. This adjustment of innovation strategy may be different for different enterprises, thus the impact effect of ETS on enterprises' green innovation differs between different types of enterprises [24]. This leads to Hypothesis 2:

H2. The promotion effect of the ETS on green innovation exhibits heterogeneity in different enterprises.

The differences between enterprises are often reflected in three aspects: capital size, equity concentration, and industry category. As such, the heterogeneity of promotion effect of the carbon ETS on green innovation can also be analyzed in three aspects, i.e., the capital size, the equity concentration, and the industry category.

Firstly, capital size of an enterprise not only reflects the enterprise's production scale, but also represents the difficulty of its endogenous and exogenous financing [25]. The resource dependence theory suggests that organizations form a demand for external resources, establish connections with the outside world, and thus obtain resources from the outside world. The stronger this demand, the closer the connection between the organization and the outside world. Enterprises with larger capital scales exhibit a stronger capacity for obtaining external financing. Sufficient capital can greatly enhance the enterprise's ability to resist risks, and the close connection with the external market enables it to accelerate the pace of its own technological progress. In this way, enterprises can maintain a comparative advantage in fierce market competition and obtain excess profits. In contrast, enterprises with smaller capital scales may face tight financial constraints and be unable to withstand the risks associated with R&D failures [26]. Moreover, small capital scale enterprises generally still be in the phase of increasing returns to scale. Instead of investing their funds in technology innovation with uncertain outcomes, it is optimal for them to expand their production scale. Therefore, the following hypothesis is proposed in this study:

H2a. The implementation of carbon ETS has a more significant promoting effect on the green innovation level of enterprises with larger capital scales.

Secondly, according to the principal-agent theory, differences arise between company operators and investors in major aspects related to the long-term development. For example, due to conflicting interests and information asymmetry, the business decisions often have differences. The concentration of corporate equity reflects this principal-agent relationship. Specifically, when the concentration of equity in a company is low, company managers have to accept external supervision from multiple parties. They often adopt aggressive strategies to enhance the company's value, thereby attracting more individual and institutional investors [27]. With the gradual increase in equity concentration, controlling shareholders tend to maximize their own interests by encroaching on the interests of other minority shareholders. There is even a motivation to "empty" the assets of listed companies that attract investors, creating a so-called "trench defense effect" [28]. Therefore, this study believes that companies with lower equity concentration have more open, transparent, and diversified corporate governance pattern. This can increase their investment in green technology and significantly increase green innovation when implementing the carbon ETS. Conversely, companies with relatively higher equity concentration are more dependent on

the decisions of management representatives, who represent the interests of major shareholders. They are more focused on short-term interests rather than long-term development, it is improbable that these companies will embark on green innovation endeavors due to the existence of the ETS. As such, we propose the following hypothesis:

H2b. The implementation of ETS has a more significant promoting effect on the green innovation level of enterprises with lower equity concentration.

Thirdly, low-carbon green production should not only be implemented in every product and every industrial process, but also from the source and throughout the entire industrial chain of production. As production methods and energy use may vary among industries and enterprises, the emission reduction methods may vary greatly among different industries and the aspects of innovation may also differ [29]. The ETS policy has different effects on green innovation incentives among different industries, which puts forward new requirements for policy strength and schemes in different industries. Therefore, this study believes that even in the pilot enterprises, there exists industry heterogeneity in the promotion effect of ETS on green innovation. As such, this study proposes the following hypotheses:

H2c. The implementation of ETS has different promoting effect on the green innovation level of enterprises in different industries.

4. Research Design and Sample Selection

4.1. The PSM-DID Method

This study focused on the impact of carbon ETS on green innovation in high-carbon enterprises, aiming to investigate the change in the green innovation level of enterprises before and after the implementation of ETS. In reality, however, there are no two identical companies, one that implements ETS policies and the other that does not. The difference in difference (DID) method divides the target enterprises into a treatment group and a control group by constructing a quasi-natural experiment [30]. The control group is used to simulate the situation of enterprises in the treatment group without implementing ETS, which is to solve the problem of "counterfactual". Meanwhile, the DID method requires the selection of the experimental sample is randomized. However, the selection of pilot provinces, cities, and emission control enterprises in China is not random, but closely related to regional development level, carbon emission level, and the characteristics of the enterprises themselves. Therefore, using DID alone to estimate the average processing effect cannot meet the framework of counterfactual reasoning models. This might lead to serious sample selection bias and endogeneity problems [31]. Propensity Score Matching (PSM) is to replace multiple covariates with a single score, thereby achieving balance in the distribution of these covariates across the treatment and control groups [29]. This can perform a randomized equilibrium treatment on confounding factors in non-randomized studies to reduce selection bias.

In addition, with the continuous development of ETS, there are differences in the processing time points among enterprises participating in ETS. The traditional PSM-DID with a single processing time point is not applicable here. As such, referring to Liu and Liu [29], this study constructs a year-by-year PSM-DID method to estimate the actual treatment effect of ETS policies on enterprises' green innovation. Based on the theoretical analysis mentioned earlier, a fixed-effects model should be used, the benchmark regression model is as follows:

$$\ln(Patent)_{it} = \alpha + \beta ETS_i \times Period_t + \gamma Z_{it} + \mu_m + v_n + \nu_t + \varepsilon_{it} \quad (1)$$

where i and t represent the company and the year, respectively. The logarithm of the number of green patents $\ln(Patent)_{it}$ is the explained variable, representing the green innovation level of company i in year t; α represents the constant term in the regression; the interaction

term $ETS_i \times Period_t$ represents the explanatory variable of policy implementation or not; and its fitted regression coefficient β reflects the impact effect of ETS policy on green innovation; Z_{it} represents the matrix of relevant control variables, which contains scale, profit, management, and maturity.

Among them, the enterprise scale is reflected by the size of capital (logarithm of the net assets, lnK) and employees (logarithm of the number of employees, lnL); profit is described by book value per share (BPS) and earnings per share (EPS); management is described through shareholding ratio of major shareholders (SR) and leverage ratio (LR); maturity is mainly reflected by the age of the enterprise (Age) and Tobin q value (TobinQ). Specifically, TobinQ mainly reflects the relationship between the market value of enterprise assets and their replacement costs. It is an important indicator for measuring whether a company's market value is overvalued or undervalued. The parameter of γ represents the fitted regression coefficient matrix of each control variable, μ_m, v_n and ν_t represent the fixed effects of region, industry and year, respectively. Meanwhile, ε_{it} is a random disturbance term that varies with individual and time.

4.2. Samples and Data Description

Given the ETS pilot policy's implementation timeframe primarily spanning 2013–2016, this research opted for a sample period spanning 2010 to 2019. Post-2019 data were deemed unsuitable due to the unforeseen disruptions caused by the global COVID-19 pandemic in 2020, which introduced unpredictable external factors affecting enterprises worldwide [32]. On the other hand, in 2010, the world gradually emerged from the impact of the US subprime crisis and the European debt crisis, and the production and operation of enterprises gradually returned to normal [33]. Therefore, the period from 2010 to 2019 is a reasonable and acceptable research time interval.

The carbon emission trading market in our country is mainly established on the basis of five major industries, namely: mining industry (S1), manufacturing industry (S2), electricity, heat, gas and water production and supply industry (S3), construction industry (S4), and transportation, warehousing and postal industry (S5). And these industries include enterprises participating in the pilot program, so we selected panel data of A-share listed companies in five high-carbon industries as the research field. During the preliminary screening of sample companies, we excluded listed firms exhibiting financial irregularities, including those marked with ST, PT, and *ST status, to ensure data integrity and reliability. In addition, companies with severe missing variables, delisted from the stock exchange during the study period, as well as those listed after 2006, were also excluded to maintain consistency in the sample and ensure comparability across firms. Although some financial and service enterprises are also included in the list of emission control enterprises, their production and emission reduction models differ greatly from traditional high-carbon enterprises and are not suitable for discussion together. After the above screening, the final dataset of this study includes 19,280 samples from 1928 listed companies from 2010 to 2019. Of which, the treatment group comprises 1260 samples sourced from 126 listed companies.

The number of green patents data is downloaded and classified from the Inco-Pat patent database. The other data of control variables mainly come from the Wind and CSMAR databases. The explained variable and the enterprise scale related control variables (net assets and the number of employees) have been logarithmically treated to reduce the possibility of covariance and heteroscedasticity. Table 1 shows the descriptive statistical results of the sample.

Table 1. Descriptive statistics of samples.

Variables	Non-Pilot Enterprises (N = 18,020)				Pilot Enterprises (N = 1260)			
	Mean	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**
ln(Patent)	0.31	0.75	0.00	2.71	0.56	2.29	0.01	2.77
BPS	5.04	9.14	0.01	19.32	5.37	1.99	0.01	18.63
EPS	1.06	1.00	0.01	5.99	0.97	1.00	0.01	5.46
SR	36.17	16.61	8.26	76.13	39.61	17.29	7.66	65.33
lnL	8.10	1.49	2.56	15.85	9.27	1.61	2.56	16.46
lnK	22.33	1.67	18.29	26.59	23.11	2.59	17.66	25.33
Age	24.02	5.85	9	43	31.25	5.14	10	42
LR	51.39	115.91	37.89	150.63	50.55	24.00	36.55	127.86
TobinQ	3.58	13.56	0.15	8.96	5.13	0.81	0.16	7.98

5. Empirical Research Results and Analysis

5.1. Baseline Regression Analysis

This study conducted a multi-period PSM on enterprises that participated in the pilot program from 2013 to 2016. According to the analysis of the significance of standard deviation and *t*-test, all absolute values of standard deviation were relatively large. Before applying PSM, the *p*-values derived from the *t*-test conducted between the treatment and control groups were strikingly proximate to zero, suggesting the presence of notable disparities in the covariates within the initial dataset. Nevertheless, the biases were significantly reduced and the *p*-values were not significant after PSM. This suggests the null hypothesis that after PSM, no statistically significant difference exists between the treatment and control groups. Consequently, the validity of the Propensity Score Matching process is affirmed. Utilizing panel data spanning from 2010 to 2019 of A-share listed companies across five key industries in China, this study delves into the influence of ETS on fostering green innovation within high-carbon enterprises.

The fixed-effects model can solve the problem of omitted variables that do not change with time or individuals through intra group dispersion information, partially addressing endogeneity issues. Therefore, this study uses the fixed-effects model in the regression model of DID. Due to the carbon ETS being implemented in pilot provinces and cities, targeting some high-carbon industries, macro shocks may mainly come from both provincial and industry levels. In addition, adding fixed effects at the enterprise level may excessively eliminate the differences in the implementation effects of pilot area enterprises [34,35]. Therefore, this study incorporates fixed effects of time province industry into the main regression model. Table 2 presents the results:

Table 2. Results of PSM-DID regression.

Variables	ln(*Patent*) M1-OLS	ln(*Patent*) M2-OLS	ln(*Patent*) M3-Tobit	ln(*Patent*) M4-Wei	ln(*Patent*) M5-Sup
$ETS \times Period$	0.1956 ***	0.1401 ***	0.1324 ***	0.1825 ***	0.1936 ***
	(6.0224)	(5.1172)	(2.6850)	(3.6501)	(3.6501)
BPS		0.0104 ***	0.0104 ***	0.0125 *	0.0125 *
		(4.3351)	(4.6774)	(1.6542)	(1.6782)
EPS		−0.0216	−0.0214	−0.0103	−0.0103
		(−1.3312)	(−1.2678)	(−0.0953)	(−0.0953)
SR		−0.0025 ***	−0.0025 ***	−0.0038 **	−0.0038 **
		(−3.7729)	(−3.9858)	(−2.5462)	(−2.5324)

Table 2. *Cont.*

Variables	ln(*Patent*) M1-OLS	ln(*Patent*) M2-OLS	ln(*Patent*) M3-Tobit	ln(*Patent*) M4-Wei	ln(*Patent*) M5-Sup
ln *L*		0.1614 ***	0.1110 ***	0.1615 ***	0.1615 ***
		(18.7646)	(15.0076)	(6.4527)	(6.4527)
ln *K*		0.1008 ***	0.0987 ***	0.1106 ***	0.1107 ***
		(11.4538)	(10.9986)	(4.3386)	(4.3386)
Age		−0.0010	−0.0010	0.0021	0.0021
		(−0.3653)	(−0.3637)	(0.7095)	(0.7095)
Lev		0.0010 *	0.0010 **	0.0013 *	0.0013 *
		(1.3627)	(2.6789)	(1.8802)	(1.8024)
TobinQ		−0.0001	−0.0001	−0.0365 *	−0.0365 *
		(−0.1028)	(−0.3846)	(−1.9906)	(−1.9906)
Constant	0.5266 ***	−2.3687 ***	−2.3672 ***	−3.1416 ***	−3.2456 ***
	(9.3406)	(−15.6028)	(−18.3651)	(−8.1090)	(−9.001)
Adj R^2	0.1106	0.1835	-	0.2302	0.2302

Note: the values in parentheses are t-values; *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

As shown in Table 2, different methods were applied to estimate the results. The coefficient of the policy interaction term $ETS_i \times Period_t$ is significantly positive under different methods, indicating that ETS has an increasing effect on the green innovation of high-carbon enterprises. This verifies the conjecture of Hypothesis 1 and the rationality of the theoretical derivation in H1.

In Column (1), there is no control variable added to the OLS regression model but after the three levels of fixed effects were controlled. Its coefficient of the interaction item was the largest among Columns (1)–(3), which may be due to the omission of important variables. So we added the eight control variables mentioned above in Columns (2)–(5). In Column (2), the coefficient of the DID estimator revealed that the green patents of the regulated industrial firms increased by 14.01% as compared with the non-pilot industrial firms. Among all control variables, size of capital (ln *K*), size of employees (ln *L*), book value per share (*BPS*) showed significant positive correlations with the green innovation of the enterprise. This indicates that, under the environmental regulation policies, some differential factors related to the enterprise itself have been effectively controlled. This result is consistent with the research by Hang et al. [36], that is, the size of the firm will amplify its impact on the output of green innovation.

Meanwhile, Column (2) shows that the shareholding ratio of the major shareholders inhibited the improvement of green technological innovation. A possible reason is that enterprises with a high SR tend to leave decision-making in the hands of a few top leaders, and therefore it is a smarter choice to purchase high value-added fixed assets rather than increasing R&D investment in the long term. Column (3) shows the results of a Tobit model used to estimate the effects of the ETS on a firm's green patents because the values of the dependent variable are mostly zero. This estimation result is roughly consistent with the OLS estimation. In Column (4), we refined the sample by excluding instances with zero matching weights, retaining only those with non-zero weights. Conversely, in Column (5), we augmented the sample by expanding the pool to include cases where the matching weights exceeded unity. Across both approaches, the empirical findings consistently demonstrated that the implementation of the ETS pilot policy had a markedly positive impact on promoting green technological innovation within industrial enterprises.

5.2. The Robustness Test

5.2.1. The Parallel Trend Test

The validation of the parallel trend assumption test for the estimated results of the model is noteworthy. This indicates that prior to policy implementation, pilot and non-pilot enterprises followed similar trends in green innovation development, thereby confirming

the validity of employing the PSM-DID model. This lends credibility to the analytical approach used and enhances the robustness of the findings regarding the effects of the ETS on green innovation development. The following regression model can be used to estimate whether exist the parallel trends between the treatment and control groups:

$$\ln(Patent)_{it} = \alpha + \sum_{k=-6}^{6} \beta_k \cdot DID_{it}^{k} + \gamma Z_{it} + \mu_m + v_n + \nu_t + \varepsilon_{it} \quad (2)$$

where DID_{it}^{k} is a series of dummy variables indicating whether the policy has occurred or not. The coefficient β_k for each year is the dynamic effect of the policy, and its significant change trend is the focus of this article. The specific results are shown in Table 3:

Table 3. The parallel trend test for the whole sample.

Period	ln(*Patent*) M3-Tobit		ln(*Patent*) M4-Wei		ln(*Patent*) M5-Sup	
	Coefficients	**t-Values**	**Coefficients**	**t-Values**	**Coefficients**	**t-Values**
Before-6	0.0324	−0.8628	0.0324	−0.8637	−0.0281	−0.3157
Before-5	0.0745	−1.0004	0.0745	−1.0982	0.0094	−0.1615
Before-4	0.0586	−0.9272	0.0586	−0.9174	−0.0092	−0.1146
Before-3	0.0701	−1.0795	0.0701	−1.1864	0.0201	−0.1494
Before-2	0.1473 **	−2.6373	0.1473 **	−2.663	0.0801	−1.3992
Before-1	0.1389 **	−2.5169	0.1389 **	−2.1617	0.0624	−1.1784
Current	0.1981 ***	−4.07462	0.1981 ***	−4.07968	0.1320 ***	−2.91346
After-1	0.1811 ***	−3.45642	0.1811 ***	−3.45103	0.1026 **	−2.35202
After-2	0.1364 ***	−3.47578	0.1364 ***	−3.4705	0.1186 **	−2.38326
After-3	0.1526 ***	−3.13467	0.1526 ***	−3.12983	0.1124 *	−2.07614
After-4	0.1226 **	−2.29955	0.1226 **	−2.29603	0.0627	−1.2936
After-5	0.1895 ***	−3.04546	0.1895 ***	−3.04084	0.1131 *	−2.09077
After-6	0.1465 **	−2.53902	0.1465 **	−2.53506	0.0815	−1.6445
Constant	−1.9626 ***	−26.7094	−2.6638 ***	−23.0069	−1.3288 ***	−17.3586
Adj R^2			0.1238		0.1139	

Note: *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

Table 3 presents the regression results of the dynamic effects of the ETS. Based on M3-Tobit and M4-Wei, this study evaluates the dynamic innovation effect of ETS using Tobit model and OLS fixed-effects model, respectively. All other control variables except for employee size ($\ln L$) are included, because the employee size statistics in the database are based on the number of employees at a time point, not changing over time. These two regressions have reached similar conclusions, that is, before the implementation of the ETS, there was no significant difference in the level of green innovation between the two groups of enterprises. Meanwhile, in the year of implementation and subsequent years, it became significantly positive at a 5% level. Based on M5-Sup, all the control variables were added to the regression model, and the coefficients are not significant before the pilot projects in various provinces and cities start in batches. This is consistent with the fact. However, the coefficients of After4 and After6 are not significant, which may be due to the innovation activity gradually encounters bottlenecks during this period. In conclusion, the results presented in Table 3 indicate that the basic model of the ETS on green innovation for high-carbon enterprises has passed the parallel trend test.

5.2.2. The Placebo Test

The above results have made it clear that enterprises participating in the ETS have a relatively higher level of green innovation, which raises the question of whether this difference is gradually emerging based on the implementation of the ETS. Therefore, a placebo test with random years was conducted to reverse verify whether the observed increase in green innovation level occurred after the implementation of the ETS. Considering the

gradual implementation characteristics of ETS, the time point for unified verification is not applicable. Therefore, this article adopts the following strategies for research:

Firstly, we conducted a random sampling simulation on the pilot enterprises. In the sampling process, we randomly selected a year for each pilot enterprise and assumed that this year was the implementation year of the ETS policy.

Secondly, set this year and subsequent years as simulated processing years, within which we assume that the enterprise has been affected by ETS. And the years before this year are considered as simulated unprocessed years, assuming that the enterprise has not been affected by ETS during these years.

Thirdly, based on this division, we constructed a new policy time dummy variable to simulate the potential impact of ETS on enterprises at different time points. To ensure the reliability and non-accidental nature of the simulation, this experiment was conducted 500 times, and the kernel density and *p*-value distribution of each estimated coefficient are shown in Figure 1 below.

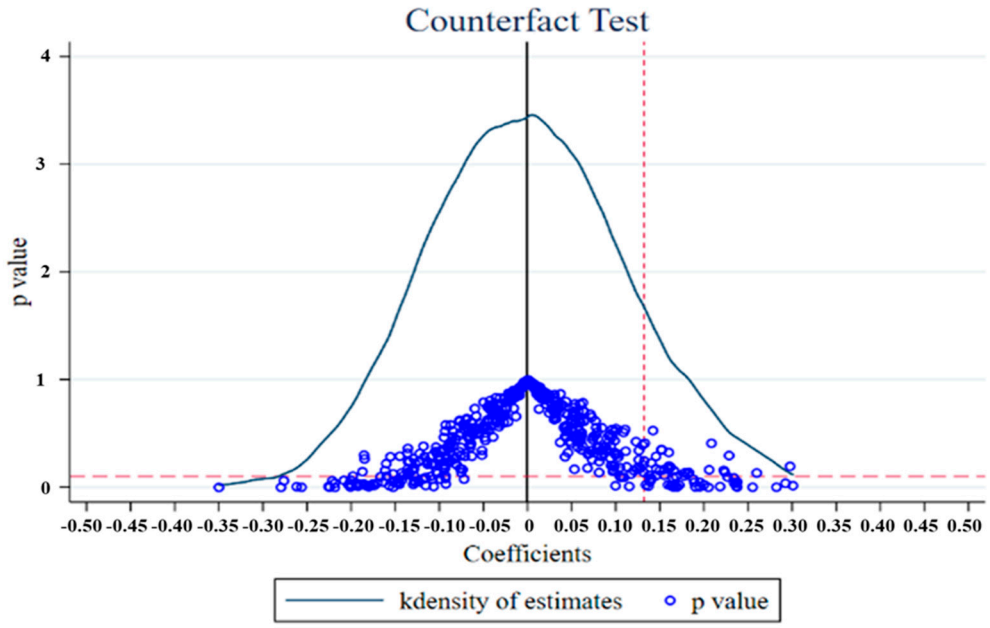


Figure 1. Results of the placebo test.

As shown in Figure 1, the vertical dashed line at x = 0.1401 signifies the actual estimated coefficient derived from the baseline regression analysis utilizing the M2-OLS methodology. The horizontal dashed line at y = 0.1, on the other hand, denotes the threshold for statistical significance, as indicated by the *p*-value boundary. From the regression results of 500 simulations, Figure 1 shows that the results estimated by the randomized year placebo test are significantly different from the actual estimated coefficient, and most of the *p*-values represented by the small circle are above 0.1. The above results indicate that the selection of occurrence time nodes for ETS in the basic study is not accidental, strengthening the robustness of the estimated results.

5.2.3. The Instrumental Variable Method Test

Because the selection of carbon emission trading pilot areas may be affected by other potential factors, which may interfere with the estimation results, the existence of random disturbance terms may make the estimation results inaccurate. In order to further overcome the influence of endogeneity, this study uses the instrumental variable method to deal with the endogeneity problem. The selection of effective instrumental variables needs to satisfy two conditions that are related to endogenous variables but not to random perturbation terms.

Following the idea of Zhang and Xi [35], this study chooses air circulation coefficient as the instrumental variable for implementing ETS pilot policies. The reason is that: firstly, when the total amount of carbon emissions is constant, the smaller the air circulation coefficient in an area, and the higher concentration of carbon dioxide. Therefore, environmental departments are more likely to choose high-carbon emission areas as pilot areas. Thus, this instrumental variable satisfies the assumption of correlation. Secondly, the air circulation coefficient is determined solely by meteorological and geographical conditions and is unrelated to random disturbances. Hence, this instrumental variable satisfies the assumption of exogeneity. The air circulation coefficient is represented by the product of wind speed and boundary layer height for each unit. Based on the atmospheric quantity model, this study constructs variables for air mobility indicators at the prefecture level in China.

As shown in Table 4, column (1) presents the first stage regression results of instrumental variables, where *iv* represents the natural logarithm of the annual mean air circulation coefficient of the city where the industrial enterprise is located. The coefficient of the interaction term $iv \times Period$ is significant, indicating a high correlation between instrumental variables and policy variables. In the second stage regression, the coefficient of the interaction term between the fitted policy variables is also significant, and it is almost consistent in direction and magnitude with the innovation effect of ETS policy in the benchmark regression, which is 14.01%. This indicates that after eliminating the endogeneity problem of non-random factors in policy selection, ETS policy can still significantly promote the improvement of green innovation level in industrial enterprises, which further verifies the robustness of the benchmark regression results.

Table 4. Results of the instrumental variable method test.

	ETT* × *Period **(1)**	**ln(*Patent*)** **(2)**
$iv \times Period$	0.0716 *** (163.0028)	
$ETS \times Period$		0.1422 *** (4.5687)
Constant	−0.0066 (−0.3125)	−1.3258 *** (−27.1628)
Time fixed effect	Y	Y
Province fixed effect	Y	Y
Industry fixed effect	Y	Y
Control variable	Y	Y
Adj R^2	0.4954	0.1343

Note: the values in parentheses are t-values; *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

5.3. Heterogeneity Analysis

The effects of ETS pilot programs may vary in practice for different companies. This study focuses on the characteristics of companies implementing ETS pilot programs, and study the differences in green innovation strategies among different types of companies based on three factors: capital size, equity concentration, and industry category. Following the idea of moderating effects, the interaction terms between heterogeneity variables and policy variables are constructed and put into the model for regression. Grouping all samples for regression analysis, rather than performing regression analysis on a subset of samples, can help eliminate inconsistencies in regression estimates and make the regression results more convincing. Therefore, in order to test the heterogeneous impact of ETS on the green innovation of different enterprises, namely the theoretical H2 proposed above, we construct heterogeneous research models as follows:

$$\ln(Patent)_{it} = \alpha + \beta_1' ETS_i \times Period_t + \beta_2' k_i \times ETS_i \times Period_t + \gamma Z_{it} + \mu_m + v_n + \nu_t + \varepsilon_{it} \quad (3)$$

$$\ln(Patent)_{it} = \alpha + \beta_1'' ETS_i \times Period_t + \beta_2'' sr_i \times ETS_i \times Period_t + \gamma Z_{it} + \mu_m + v_n + \nu_t + \varepsilon_{it} \quad (4)$$

$$\ln(Patent)_{it} = \alpha + \beta_1''' IndB \times ETS_i \times Period_t + \beta_2''' IndC \times ETS_i \times Period_t + \beta_3''' IndD \times ETS_i \times Period_t + \beta_4''' IndE \times ETS_i \times Period_t + \beta_5''' IndG \times ETS_i \times Period_t + \gamma Z_{it} + \mu_m + v_n + \nu_t + \varepsilon_{it} \quad (5)$$

where k is a grouping variable representing the capital scale in Equation (3), with $k = 1$ representing a larger scale of corporate capital, higher than the median of all corporate capital scales, and $k = 0$ representing the remaining enterprises. The variable of sr represents a grouping variable for corporate equity concentration in Equation (4), measured by the shareholding ratio of major shareholders, also using the median shareholding ratio of major shareholders as the division standard. The term $sr = 1$ represents a company with lower equity concentration and more diversified corporate governance, while $sr = 0$ represents a company with more centralized corporate governance. In Equation (5), $IndB$, $IndC$, $IndD$, $IndE$ and $IndG$ respectively represent the five major national economic sectors involved in the research sample companies.

As such, in Equation (3), β_1' represents the magnitude of the increase or decrease in the level of green innovation in enterprises with lower capital scale under the influence of the ETS. If β_2' is significantly different from zero, it indicates that under the ETS, the level of green innovation varies among enterprises with different capital scale levels. The explanation of sr in Equation (4) is similar. In Equation (5), the policy interaction term was divided into five interaction terms according to the classification of national economic industries, representing the green innovation effects of ETS in the five industries. The coefficients in front of each term represent the magnitude of the increase or decrease in the level of green technology innovation in the industry under the influence of the ETS. The coefficients (i.e., β_1''', β_2''', β_3''', β_4''', and β_5'''), respectively, represent the extent to which the green innovation level of enterprises in the corresponding industry has increased or decreased under the action of ETS pilot policies. The regression results are shown in Table 5:

Table 5. Heterogeneous effects of ETS pilot policy on green innovation.

Variables	ln(*Patent*)	ln(*Patent*)	ln(*Patent*)
$ETS \times Period$	−0.2081 ***	0.1001	
	(−4.073)	(1.2483)	
$k \times ETS \times Period$	0.3962 ***		
	(8.2452)		
$sr \times ETS \times Period$		0.2031 ***	
		(5.7261)	
$IndB \times ETS \times Period$			3.1594 ***
			(12.0456)
$IndC \times ETS \times Period$			0.3390 ***
			(3.4855)
$IndD \times ETS \times Period$			0.1801 *
			(0.1743)
$IndE \times ETS \times Period$			0.4833 **
			(3.0813)
$IndG \times ETS \times Period$			−0.4410 ***
			(−3.8460)
Constant	−0.6962 ***	−3.1415 ***	−2.2151 ***
	(−15.2431)	(−13.9124)	(−15.7623)
Adj R^2	0.1536	0.1522	0.1304

Note: the values in parentheses are t-values; *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

From the perspective of capital scale heterogeneity, enterprises with different capital scales often have different responses to innovation even when facing the same environmental regulation system. As shown in Table 5, the estimated coefficient values of β_1' and β_2' in Equation (3) are -0.2081 and 0.3962, respectively, and both have passed the 1% significance test. This indicates that enterprises with lesser capital tend to curtail their green innovation endeavors by approximately 20.81% as a means to comply with emission reduction targets, whereas those with ample capital exhibit significantly different behavior patterns in this regard. When facing the ETS, large enterprises tend to carry out 39.62% more green innovation than small enterprises. This means that under the pressure of market-oriented environmental regulations, large enterprises can choose to strengthen 18.81% of green innovation on their own, rather than purchasing emission quotas. On the one hand, large enterprises demonstrate strong mortgage guarantee capabilities through their sound financial management system, which greatly promotes the diversification of their financing channels and significantly enhances their ability to diversify and resist innovation risks. On the other hand, large enterprises have gained strong bargaining power in the supply chain due to their economies of scale and market dominance, further consolidating their market influence. In contrast, small-scale companies are often unwilling to increase their green innovation investment in order to alleviate financial and cost pressures. This result further suggests that implementing ETS for enterprises with larger capital scales is more conducive to the generation of green innovation, and the innovation compensation effect can be achieved. However, for enterprises with small capital scales, the compliance costs are too high, resulting in a crowding-out effect of green technology innovation.

From the perspective of equity concentration heterogeneity, enterprises with different equity concentration often have different responses to innovation even when facing the same environmental regulation system. As shown in Table 5, the estimated coefficient values of β_1'' and β_2'' in Equation (4) are 0.1001 and 0.2031, respectively. This means the ETS pilot policy has promoted green innovation in 10.01% and 20.31% of companies with higher and lower equity concentration, respectively. Specially, companies with low equity concentration are more inclined to invent green innovation, with a 10.30% increase in green innovation output compared to companies with high equity concentration companies. Companies with high equity concentration, the division of labor and checks and balances within the governance layer are not clear or superficial. The power holders may only rely on their own judgment of current environmental regulation policies to adjust production scale, which may underestimate the long-term benefits of green technology innovation. In contrast, companies with low equity concentration have a relatively significant modular division of labor, which reduces the degree of information asymmetry and eases the relationship between delegation and agency. In the process of strategic choice, companies with low equity concentration tend to have a longer-term perspective and may place more emphasis on the importance of green technology innovation.

In the context of industrial heterogeneity, it is evident that various industries possess distinct production methodologies and strategies for achieving emission reductions, each tailored to their unique circumstances. Table 5 shows the detailed impact of ETS on green innovation in five major industries. In S1, S2, and S4, ETS has played positive roles in stimulating green innovation to some extent. There is no significant change in green innovation in S3, while in S5, after implementing ETS, green innovation level has actually decreased. Specially, S1, S2, and S4 are all high-carbon-emitting industries, accounting for more than 70% of the nation total CO_2 emissions. A larger emissions volume naturally requires more green emission reduction technologies to achieve the goal of carbon emission reduction. Otherwise, only expensive quotas or production cuts can be purchased, which brings considerable costs and consequences. This creates a virtuous cycle in innovation input-output for these industries. The poor green innovation effect of the ETS policy in S3 may be due to nearly half of the industry's innovation expenditure being directed towards the procurement of machinery, equipment, and software, rather than internal research and development. On the contrary, the ETS has had a negative impact on the green innovation

of S5. This is because the industry mainly relies on advanced transportation equipment and reasonable scheduling to save energy and reduce emissions, thus performing poorly in green technology innovation.

With limited financial resources, companies divert spending that would otherwise have been spent on innovation into the acquisition of machinery and software, thereby reducing long-term investment in green technology research and development and innovation. This "crowding out" effect of capital allocation causes resources that might otherwise be used for green technology innovation to be replaced by other more urgent expenditures, thus inhibiting the green technology progress of enterprises in related industries. Therefore, on the one hand, the government should encourage and support enterprises to obtain funds through diversified financing channels, so as to reduce the financial pressure of enterprises and make them have more resources to invest in green technology innovation. On the other hand, further improve the carbon trading market mechanism to ensure fair, transparent and efficient operation of the market. Through reasonable carbon price signals, enterprises are guided to actively carry out energy conservation and emission reduction and green technology innovation, and achieve a win–win situation of economic and environmental benefits.

6. Conclusions and Limitations

6.1. Conclusions

Green technology innovation is an important driving force for low-carbon development of enterprises. As a market-based environmental policy to promote greenhouse gas emission reduction, whether carbon emission trading scheme (ETS) can encourage enterprises to carry out green technology innovation deserves further study. Utilizing a comprehensive dataset of Chinese A-share listed companies spanning five key sectors from 2010 to 2019, this study employs a multi-period PSM-DID model to rigorously examine the causal nexus between ETS and green innovation within high-carbon industries. Additionally, a nuanced heterogeneity analysis is undertaken, delving into the differential impacts across three pivotal dimensions: capital intensity, equity concentration, and industrial classification. The core findings of this study are succinctly encapsulated as the following two aspects:

Firstly, the ETS has a significant promoting effect on green innovation in high-carbon enterprises, with an increase of 14.01% even after adding control variables at the enterprise level. In addition, under different regression methods, the results are consistent. In order to further test the robustness of the results, this study adopts the parallel trend test, the placebo test of random years, and the instrumental variable method test. The above tests showed that ETS has indeed a significantly positive impact on green technology innovation of high-carbon enterprises. That is to say, the innovation compensation effect considered in Porter's hypothesis does exist in enterprises implementing ETS, and the effect of innovation compensation effect is greater than that of innovation crowding-out effect.

Secondly, enterprises with different characteristics have heterogeneity in the impact of ETS implementation on green technology innovation. Specifically, enterprises with smaller capital scales have reduced some green innovations when subjected to market-oriented environmental regulation policies, while enterprises with larger capital scales have increased their output of green innovation. The level of green innovation in enterprises with lower equity concentration is significantly better than that in enterprises with higher equity concentration. Moreover, the green innovation effect of ETS is also diverse in different industries. In S1, S2 and S4, ETS has positive stimulating effects on green innovation to a certain extent. Moreover, there is no significant change in green innovation in the S3. However, the S5, on the other hand, experienced a decrease in green innovation after ETS implementation.

After clarifying the transmission mechanism and the impact of ETS on enterprises' green innovation, this study puts forward the following policy recommendations.

Firstly, due to the fact that ETS can effectively promote high-carbon enterprises to promote green innovation. Regulated enterprises should consolidate their market competitiveness through green innovation, promptly and precisely adjust their development strategies and positioning, and transform their previous disadvantage of high emissions into the advantage of green production. For instance, such enterprises can actively shift to industries with low pollution and emissions, e.g., renewable energy. For enterprises that are not under the supervision for the time being, they should learn from the advanced green technologies of industry leaders, actively participate in the ETS market. Through attracting external investments, they should promote a transition towards more advanced and resource-saving production modes. Furthermore, they should actively seek cross-regional cooperation with enterprises in different regions to strengthen the regional spillover effect of green technologies, thereby making the positive impact of green technologies more extensive and profound.

Secondly, due to the fact that the promotion effect of the ETS on green innovation exhibits heterogeneity in different enterprises. For different types of enterprises, practical and feasible green technology innovation solutions should be proposed to cope with ETS policies, rather than a one size fits all approach. In industries such as mining (S1), manufacturing (S2), and construction (S4), the coverage of ETS should be further expanded to maximize the proactive role of these enterprises in green innovation. For enterprises in naturally monopolistic industries like electricity, heat, gas, and water production and supply (S3), they can increase investment in green innovation by applying for government policy support, such as tax incentives and green innovation funds. For enterprises in transportation, warehousing, and postal services (S5), due to their apparent innovation crowding-out effect, staff should be provided with training related to carbon accounting to gain insights into their production processes and energy consumption. This will enable them to formulate mid-to-long-term carbon emission plans. In the short term, enterprises should ensure that their carbon emissions match the quotas allocated by the government; in the long term, they should strive to achieve additional revenue by selling quotas. Meanwhile, when making strategic choices for green innovation, enterprises need to further improve the equity allocation system, and reduce the agency problems caused by information asymmetry.

6.2. Limitations

This study takes enterprise heterogeneity as the starting point to analyze whether EST can promote green innovation in high-carbon industries and its impact mechanism. However, there are still some limitations. Due to the lagging nature of policy effects and limitations in data, this study did not explore the impact of policy lag on green innovation. With further improvement of data in the future, the impact of policy lag on corporate green innovation should also be explored and studied. At the same time, due to the availability of corporate data, the analysis of corporate heterogeneity in this study is not very comprehensive. In the future, we will continue to collect data at the enterprise level to explore the impact mechanism of EST on green innovation and the impact of enterprise heterogeneity from more dimensions.

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References

1. Hu, Y.J.; Zhang, R.; Wang, H.; Li, C.; Tang, B.J. Synergizing policies for carbon reduction, energy transition and pollution control: Evidence from Chinese power generation industry. *J. Clean. Prod.* **2024**, *436*, 140460. [CrossRef]
2. Yu, F.; Zheng, S.; Zheng, S.; Guo, C. Does carbon ETS affect the distribution of labor's slice of the factor income pie? From the low carbon transition perspective. *Energy Econ.* **2024**, *134*, 107569. [CrossRef]
3. Xian, Y.; Li, N.; Zhao, M. Market potential and the industrial sectors inclusion sequence in China's national carbon emission trading: From the perspective of maximizing gains. *J. Clean. Prod.* **2024**, *435*, 140511. [CrossRef]
4. Sun, K.; Zhou, F.; Liu, X. Study on the impact of emission trading scheme on technological progress of power generation sector in China: A perspective from energy transition. *Energy* **2024**, *302*, 131750. [CrossRef]
5. Zhang, H.; Zhang, L. Public support and energy innovation: Why do firms react differently? *Energy Econ.* **2023**, *119*, 106528. [CrossRef]
6. Sun, Y.; Shen, S.; Zhou, C. Does the pilot emissions trading system in China promote innovation? Evidence based on green technology innovation in the energy sector. *Energy Econ.* **2023**, *126*, 106984. [CrossRef]
7. Fang, K.; Zhang, Q.; Song, J.; Yu, C.; Zhang, H.; Liu, H. How can national ETS affect carbon emissions and abatement costs? Evidence from the dual goals proposed by China's NDCs. *Resour. Conserv. Recycl.* **2021**, *171*, 105638. [CrossRef]
8. Wu, L.; Zhu, Q. Has the Emissions Trading Scheme (ETS) promoted the end-of-pipe emissions reduction? Evidence from China's residents. *Energy* **2023**, *277*, 127665. [CrossRef]
9. Zhang, Z. Carbon emissions trading in China: The evolution from pilots to a nationwide scheme. *Clim. Policy* **2015**, *15* (Suppl. 1), S104–S126. [CrossRef]
10. Jia, L.; Zhang, X.; Wang, X.; Chen, X.; Xu, X.; Song, M. Impact of carbon emission trading system on green technology innovation of energy enterprises in China. *J. Environ. Manag.* **2024**, *360*, 121229. [CrossRef]
11. Han, Y.; Zhe, C.; Liu, X. Is the carbon emissions trading system conducive to the urban green technology innovation level? Evidence from China. *Energy Rep.* **2023**, *9*, 3787–3799. [CrossRef]
12. Zhou, F.; Wang, X. The carbon emissions trading scheme and green technology innovation in China: A new structural economics perspective. *Econ. Anal. Policy* **2022**, *74*, 365–381. [CrossRef]
13. Liu, Z.; Sun, H. Assessing the impact of emissions trading scheme on low-carbon technological innovation: Evidence from China. *Environ. Impact Assess. Rev.* **2021**, *89*, 106589. [CrossRef]
14. Lin, B.; Ma, R. Green technology innovations, urban innovation environment and CO2 emission reduction in China: Fresh evidence from a partially linear functional-coefficient panel model. *Technol. Forecast Soc.* **2022**, *176*, 121434. [CrossRef]
15. Zhuang, Y.; Bi, Y.; Song, F.; Chen, J. Research on the Impact of Green Credit Policies on Green Innovation of Heavy Polluting Enterprises: A Case Study of Sichuan Province. *J. Innov. Dev.* **2024**, *6*, 71–77. [CrossRef]
16. Wu, D.; Jia, W.; Xie, Y. The impact of environmental information disclosure on green innovation in extractive enterprises: Promote or crowd out? *Extr. Ind. Soc.* **2023**, *14*, 101247. [CrossRef]
17. Zhao, A.; Wang, J.; Sun, Z.; Guan, H. Environmental taxes, technology innovation quality and firm performance in China—A test of effects based on the Porter hypothesis. *Econ. Anal. Policy* **2022**, *74*, 309–325. [CrossRef]
18. Chen, R.; Howley, P.; Kesidou, E. The impact of ETS on Productivity in developing economies: A micro-econometric evaluation with Chinese firm-level data. *Energy Econ.* **2024**, *131*, 107376. [CrossRef]
19. Levinson, A.; Scott Taylor, M. Unmasking the Pollution Haven Effect. *Int. Econ. Rev.* **2008**, *49*, 223–254. [CrossRef]
20. Peri, G. Determinants of knowledge flows and their effect on innovation. *Rev. Econ. Stat.* **2005**, *87*, 308–322. [CrossRef]
21. Zhang, D.; Jin, Y. R&D and environmentally induced innovation: Does financial constraint play a facilitating role? *Int. Rev. Financ. Anal.* **2021**, *78*, 101918.
22. Lee, J.S.; Hsieh, C.J. A research in relating entrepreneurship, marketing capability, innovative capability and sustained competitive advantage. *J. Bus. Econ. Res.* **2010**, *8*, 109. [CrossRef]
23. Cao, H.; Zhao, Y.; Yuan, L.; Li, K. Does legislation promote technological innovation in renewable energy enterprises? Evidence from China. *Energy Policy* **2024**, *188*, 114111. [CrossRef]
24. Chen, Z.; Zhang, X.; Chen, F. Do carbon emission trading schemes stimulate green innovation in enterprises? Evidence from China. *Technol. Forecast. Soc. Change* **2021**, *168*, 120744. [CrossRef]
25. Li, C.; Wang, Y.; Zhou, Z.; Wang, Z.; Mardani, A. Digital finance and enterprise financing constraints: Structural characteristics and mechanism identification. *J. Bus. Res.* **2023**, *165*, 114074. [CrossRef]
26. Jiang, Z.; Xu, C. Policy incentives, government subsidies, and technological innovation in new energy vehicle enterprises: Evidence from China. *Energy Policy* **2023**, *177*, 113527. [CrossRef]
27. Guo, B.; Huang, X. Digital transformation tone signal and the cost of equity: Evidence from Chinese listed companies. *Financ. Res. Lett.* **2024**, *59*, 104720. [CrossRef]

28. Niu, F.; Li, M.; Li, Y.L. Media reporting, company IPO and audit fees—Empirical evidence from Chinese listed companies. In *Management, Information and Educational Engineering*; CRC Press: Boca Raton, FL, USA, 2015; pp. 1187–1192.
29. Liu, J.; Liu, X. Effects of carbon emission trading schemes on green technological innovation by industrial enterprises: Evidence from a quasi-natural experiment in China. *J. Innov. Knowl.* **2023**, *8*, 100410. [CrossRef]
30. Dai, X.; Wang, F. Does the high-and new-technology enterprise program promote innovative performance? Evidence from Chinese firms. *China Econ. Rev.* **2019**, *57*, 101330. [CrossRef]
31. Zhang, Y.; Yang, S.; Ye, W.; Faries, D.E.; Lipkovich, I.; Kadziola, Z. Practical recommendations on double score matching for estimating causal effects. *Stat. Med.* **2022**, *41*, 1421–1445. [CrossRef]
32. Liu, Y.; Zhang, H.; Chen, D.Q. On the economic implications of international travel restrictions: Evidence from Chinese MNEs' firm value. *J. Bus. Res.* **2024**, *170*, 114354. [CrossRef]
33. Zhang, Y.; Xu, L. Analysis of the impact and path of the European debt crisis on China's exports to Europe. *Eur. Stud.* **2014**, *32*, 100–116.
34. Zhang, W.; Xi, B. The effect of carbon emission trading on enterprises' sustainable development performance: A quasi-natural experiment based on carbon emission trading pilot in China. *Energy Policy* **2024**, *185*, 113960. [CrossRef]
35. Zhang, C.; Quan, B.; Tang, J.; Cheng, K.; Tang, Y.; Shen, W.; Su, P.; Zhang, C. China's wastewater treatment: Status quo and sustainability perspectives. *J. Water Process Eng.* **2023**, *53*, 103708. [CrossRef]
36. Hang, J.; Wang, M.; Zhou, M. The Misallocation Cost of Inefficient Environmental Regulation: Evidence from China. 2023. Available online: https://ssrn.com/abstract=4435038 (accessed on 2 May 2023).

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Navigating Environmental Tax Challenges: Business Strategies for Chinese Firms Sustainable Growth

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Abstract: The environmental tax burden on Chinese firms is continuously increasing. How do firms respond to environmental tax pressure to achieve sustainability? This study aims to investigate whether environmental tax burden affects firms' total factor productivity (TFP), an important indicator of sustainable development. Utilizing panel data of Chinese A-share listed firms from 2018–2022, we find that environmental tax burden positively impacts Chinese firms' TFP. Interestingly, the impact of environmental tax burden on TFP is mediated through fixed asset investment rather than technological innovation. This indicates that in the short term, the pressure of environmental tax on Chinese firms has not triggered the Porter Effect. Additionally, this effect is stronger in larger firms, non-state-owned firms, and sample firms with weaker financial constraints and lower transaction costs. Therefore, different firms can flexibly adopt different business strategies to achieve sustainable development when facing environmental tax burden.

Keywords: environmental tax burden; total factor productivity; technological innovation; fixed assets investment

1. Introduction

China's targets of carbon peaking by 2030 and achieving carbon neutrality by 2060 represent a commitment to global sustainability. Since the inception of the environmental tax on 1 January 2018, China has employed this fiscal mechanism as a key instrument in reducing pollution and emissions. The environmental tax, with enhanced administrative efficacy and regulatory enforceability, surpasses the previous pollution discharge fee in compelling high-polluting and energy-intensive firms to transform and upgrade, aligning with dual goals of emission reduction and high-quality economic growth.

A growing number of academic studies have examined the association of corporate environmental behavior with production efficiency and developed different opinions. The "Porter hypothesis" points out that proactive environmental regulations within firms can catalyze innovation and offer competitive advantages, thereby enhancing production efficiency and operational outcomes [1,2]. Conversely, the "restriction hypothesis" argues that strict environmental regulations impose additional cost burdens on firms, possibly hindering improvements in production efficiency and performance [3,4]. Furthermore, the "uncertainty hypothesis" suggests that the economic consequences of corporate environmental actions are uncertain [5,6].

In the past decades, China has implemented various environmental regulations measures to deal with the adverse effects of ecological pollution [7]. In the early 1970s, the Chinese government mainly adopted an administration-based ecological policy, levying environmental penalties and pollutant discharge fees. The penalty or fee system has urged polluters to cut emissions [8]. However, the pollution discharge fee system primarily imposes administrative penalties for excessive emissions, which makes no distinction between light and heavy polluters [9]. Hence, the former had no incentive to cut emissions.

The pollution is not controlled as expected in high-polluting industries, and the penalty is relatively small for enterprises in lucrative production activities. Therefore, the central authorities attempted to move from a fee to a tax scheme, carrying out market-based environmental regulation. In 2007, the Ministry of Environmental Protection of China initiated a comprehensive study on environmental taxation reform measures, leading to enacting the Environmental Protection Tax Law in 2016, officially taking effect on 1st January 2018. The environmental tax has a more authoritative effect than the pollution discharge fee [10].

In terms of environmental tax in China, prior literature has utilized the event shock of transitioning pollutant discharge fee to environmental tax (abbreviated as "fee to tax") to examine policy effects on corporate performance [11], corporate innovation [12], and corporate transformation and upgrading [13]. Existing research primarily examines policy effects at the event of "fee to tax" using methods like difference-in-differences but lacks studies on how firms choose strategies in response to environmental tax pressure.

Generally, the tax reform significantly increases compliance costs for firms [14]. Faced with the continuously increasing environmental tax burden, firms are unlikely to remain inactive. In order to reduce costs and improve productivity, firms can choose different environmental strategies to achieve sustainable development. Based on institutional theory, firms can choose a proactive environmental strategy, such as technological innovation. This is a sustainable but high-risk environmental strategy. Additionally, firms can also opt for reactive environmental strategies, such as purchasing green machinery and equipment, and developing new environmentally friendly products. Such fixed asset investments are an immediate strategy that can meet short-term environmental requirements, but they require a substantial amount of funds. Therefore, how will firms in China choose business strategies to improve their production efficiency?

To address this question, we use panel data of A-share listed firms from 2018 to 2022 in China to investigate the association of environmental tax burden on firms' total factor productivity. We find environmental tax burden positively affects firms' TFP, indicating that the environmental tax enhances corporate environmental efforts and forces green transformation. Moreover, the way in which environmental tax pressure affects the production efficiency of firms is through investment in fixed assets rather than technological innovation. This implies that environmental regulations force firms to invest in fixed assets to meet emission standards in the short term. Besides, we also discuss different situations about the association of environmental tax burden on firms' total factor productivity. Results show that large-scale firms are more capable of alleviating the increase in environmental tax costs through measures such as replacing equipment, leading to a more pronounced improvement in firms' TFP. Secondly, non-state-owned firms are more sensitive to increases in environmental tax costs and are likely to take proactive measures to enhance their TFP. In addition, in samples of firms with weaker financing constraints and lower transaction costs, the positive effect of the environmental tax burden on TFP is more significant.

This study contributes to the existing literature in two ways. First, the choice of environmental policy instruments has been extensively debated since Pigou's seminal contribution of using environmental taxes to internalize welfare losses from externalities [15]. From a micro perspective, the famous "Porter hypothesis" suggests environmental regulations stimulate corporate innovation, improving productivity and investment. However, existing empirical evidence on corporate behavior and performance provides conflicting guidance. Using samples and data from China, this study shows environmental tax burden promotes corporate production efficiency, but its mechanism of action is not through technological innovation but through fixed asset investment. This finding enriches the literature on the relationship between corporate environmental behavior and production efficiency, providing evidence outside the "Porter hypothesis". Second, some papers discussing this topic using Chinese samples and data are mainly based on the "fee-to-tax" reform event [7,10], using the difference-in-differences method to examine the economic consequences of environmental taxes, which makes it difficult to explain the specific environmental tax burden faced by firms. This paper takes the amount of environmental tax

paid as an indicator of the firm's environmental tax burden and, based on institutional theory, demonstrates the impact and strategies when firms face the pressure of environmental tax.

This study has significant theoretical and practical implications. Theoretically, this work supplements the literature on environmental tax reform effects and introduces the concept of environmental tax burden and a measurement method. Using empirical data from China, the study shows environmental tax burden enhances total factor productivity primarily through fixed asset investments, providing evidence outside the "Porter hypothesis" to enrich existing literature on environmental taxation and corporate performance. Practically, our findings provide managerial implications for practitioners and policymakers. It helps firms in practice to identify the best strategies for coping with the environmental tax burden, thereby assisting them in achieving the dual goals of energy conservation and stable performance. Furthermore, the research findings are also beneficial for policymakers to refine the environmental tax system, stimulate corporate innovation potential, and promote economic growth and emission reduction.

This paper is structured as follows. Section 2 introduces the institutional background of the environmental tax and develops the research hypotheses. Section 3 is the research design, which mainly introduces the sample, model, and variable measurement. Section 4 presents the main results of the empirical analysis and the robustness results. Section 5 further analyzes the mediating results and heterogeneous results on the relationship between the environmental tax burden and total factor productivity. Section 6 is the discussion and conclusion.

2. Institutional Background and Hypothesis Development

With increasing focus on climate change in recent decades, understanding the effects of environmental regulations on productivity is crucial for designing effective environmental tax reforms. This section outlines the development of environmental tax systems and presents details on the implementation of China's environmental tax system. It also introduces the main hypotheses of this study.

2.1. Institutional Background

Environmental regulations are a major instrument to encourage firms to take environmental protection actions, mainly including command and control environmental regulations (e.g., pollutant discharge fees) and market-based environmental regulations (e.g., environmental taxes, tradable permits).

For a long time, command-and-control environmental regulations have been the primary instrument. Drawing on developed countries' experiences, China established a pollution discharge fee system in 1979 and has since introduced a series of regulation systems to levy fees on firms for pollution discharge, aiming to control major industrial pollutants' emission levels. Previous research has found that pollution discharge fees actively promote pollution emission reductions. However, due to low fee collection standards and enforcement issues, there are concerns and even doubts from the government and all sectors of society about the pollution discharge fee system's effectiveness in pollution control [16–18].

Starting from the 1990s, environmental taxes as an important tool of market-based environmental regulations gradually gained popularity [15]. According to Pigou's tax principle, environmental taxes target the negative externalities caused by corporate environmental pollution and can effectively encourage enterprises to reduce pollution by internalizing the unit cost of pollution emissions. Unlike other environmental policy tools, environmental taxes not only restrict environmental pollution but also provide additional revenue to offset economic losses, commonly referred to as the environmental taxes' double dividend effect [19–21].

After implementing the reform and opening up policy, China has become one of the world's leading economies with high economic growth rates and has achieved significant

economic development. However, this growth has led to severe resource and environmental issues. The emissions of major pollutants have exceeded the environment's capacity, and environmental pollution and ecological destruction have become the main bottlenecks to the sustainable development of the economy. Therefore, continuously improving the ecological environment and maintaining economic growth has become a key strategic goal for Chinese enterprises and the government [22]. Against this backdrop, the Chinese government has attempted market-based environmental regulation, and in 2016, formulated the "Environmental Protection Tax Law", which officially came into effect on 1 January 2018, based on the good governance effects achieved by environmental taxes in some countries and regions.

China's environmental tax, as stated in the "Environmental Protection Tax Law of the People's Republic of China", focuses on pollutants including air pollutants, water pollutants, solid waste, and noise. The basis for taxation is the taxable pollutant emissions of enterprises, resulting in different environmental tax burdens for enterprises with varying levels of pollutant emissions. Although China allows each region to set different environmental tax collection standards based on its own conditions, most regions apply the minimum standards for collecting environmental taxes. Therefore, whether the current standards for environmental tax collection are effective in achieving China's double dividend is worth studying.

2.2. Hypothesis Development

Environmental taxes are a market-based regulation and an effective, preventive, and long-term environmental economic policy tool. It is a vital component of the environmental policy system. This paper examines the mechanism and impact of the environmental tax burden on total factor productivity based on theories such as the related research of institutional theory and the Porter hypothesis.

2.2.1. Environmental Tax Burden and Total Factor Productivity

As the global commitment to green development intensifies and the capacity of resources and the environment to sustain economic activities diminishes, firms are faced with increasingly stringent environmental regulations. Environmental taxation serves as a prototypical regulatory tool that significantly impacts corporate operations [23]. Typically, to comply with environmental regulations, firms must pay taxes and fees associated with their energy consumption and the emission of pollutants, incurring a cost of compliance [24]. The "restriction hypothesis" argues that strict environmental regulations impose additional cost burdens on firms, possibly hindering improvements in production efficiency and performance [3,4,25,26]. Pollution-intensive firms may even have to passively reduce their production activities in the short term to meet stringent environmental standards temporarily [27]. In addition, the "pollution haven hypothesis" claims that firms relocate to countries with weak environmental standards when environmental taxes rise, reducing profits, productivity, and inputs by limiting production possibilities [28]. Consequently, environmental tax directly increases the average fixed costs of firms, adversely affecting their total factor productivity.

Conversely, the "Porter hypothesis" suggests that appropriate environmental regulations can promote corporation innovation and the innovation will even offset the corporation loss caused by environmental regulations and improve corporation competitiveness [1,2,29–31]. Similarly, the "factor endowment hypothesis" suggests that employing available clean natural resources improves production possibilities and productivity [32]. So, from a dynamic perspective, firms are reluctant to witness a decline in total factor productivity (TFP) in the pursuit of sustainable development. Environmental regulations have the potential to bolster corporate environmental consciousness and provide incentives for firms to offset compliance costs through enhancements in production processes or by adopting environmentally friendly equipment [10,33]. As a result, environmental regulations are not only unlikely to diminish TFP but may also confer a competitive advantage.

However, only well-designed environmental regulations can incentivize firms to enhance productivity. For instance, in systems of pollutant discharge fees, firms lack subjective motivation to improve processes and increase environmental investment, and there is spatial heterogeneity across different regions in China [34]. Since administrative penalties occur sporadically during inspections and involve relatively low amounts. Besides, the emissions spillover is not taken into the pollutant discharge fee system [9]. Compared to pollutant discharge fees, environmental tax is directly calculated based on discharge amount, with more stringent regulatory measures. Referring to the work of Kochhar and David (1996) and so on, using competing hypotheses in empirical analysis can effectively evaluate and weigh multiple possible explanations or hypotheses, reduce cognitive biases, enhance the accuracy of the analysis, and achieve multidimensional interpretations [35]. So, based on the existing literature and the analysis in this study, we propose the following competing hypotheses:

Hypothesis 1a (H1a). *The environmental tax burden is positively associated with firms' TFP.*

Hypothesis 1b (H1b). *The environmental tax burden is negatively associated with firms' TFP.*

2.2.2. The Mediating Roles of Technological Innovation and Fixed Asset Investment

Institutional theory has risen to prominence as a popular and powerful explanation for organizational behavior [36,37]. In the past, many excellent papers have been based on institutional theory to discuss various topics such as CSR (Corporate Social Responsibility), innovation [38], organizational culture [39], and entrepreneurship [40]. This study aims to use institutional theory to analyze the sustainable business strategies of Chinese firms in response to environmental tax challenges. In the institutional theory, organizations are influenced by normative pressures arising from the state or organization itself. Under these conditions, these pressures guide organizations to respond proactively or reactively by adhering to legitimated elements [41]. Environmental tax is a typical form of institutional pressure, which often requires firms to divert attention from operational performance to cope. So, when a firm is aware of increased production costs, it typically adopts two strategies to address the situation: On one hand, with the increase in environmental tax burdens, firms may allocate more resources to technological innovation, exploring eco-friendly materials and processes [42,43]. This is a sustainable and proactive business strategy. On the other hand, firms may purchase relatively environmentally friendly production equipment and materials, reflecting increased fixed asset investment [10,33,44]. This is a real-time and reactive business strategy. Both approaches can alter production inputs, enhancing efficiency. Therefore, we propose the following hypotheses:

Hypothesis 2 (H2). *Technological innovation strengthens the relationship between the environmental tax burden and firms' total factor productivity.*

Hypothesis 3 (H3). *Fixed asset investment strengthens the relationship between the environmental tax burden and firms' total factor productivity.*

3. Research Design

The research design primarily introduces the research sample, data sources, variable definitions, and the empirical model.

3.1. Sample and Data

The sample includes all A-share firms listed on the Shanghai and Shenzhen stock exchanges from 2018 to 2022, following China's implementation of the Law of Environmental Protection Taxation on 1 January 2018 (The Shanghai and Shenzhen A-share listed markets are the largest stock trading markets in China, encompassing listed companies from a wide range of industries. Using Shanghai and Shenzhen A-share listed firms as samples can

well represent the overall situation of Chinese listed firms. Besides, data on public firms are relatively more reliable because these firms are required by law to disclose accurate financial information in their annual reports and these reports must meet international standards [45,46]). Data is sourced from the China Stock Market & Accounting Research (CSMAR) database. We excluded firms in the financial industry, those categorized as ST, *ST, or PT, and any samples with abnormal or missing data. We also winsorized all continuous variables at the 1st and 99th percentile to mitigate outliers' influence on empirical results.

3.2. Variable Definitions

Total Factor Productivity (TFP) is an indicator used to measure output growth from increased factor inputs like capital and labor. Unlike traditional indicators measuring total "growth", this index better captures enterprise development quality. Due to simultaneity bias and sample selection bias in TFP calculated by OLS, we adopt TFP calculated by OP and LP methods as firm development quality measurement indices [47,48].

Environmental tax burden (LnEnvtax) is an indicator constructed in this paper, used to represent the environmental tax pressure faced by firms. LnEnvtax is measured by taking the natural logarithm of the amount of environmental tax payable. The increase in the amount of environmental tax payable will lead firms to bear a heavier economic burden. In addition, for the robustness check, we also adopted the ratio of the amount of environmental tax payable divided by the amount of tax payable (Envtax).

We control for the following variables based on prior research [6,8,11–13], mainly including TOP1 (largest shareholder's share percentage), Growth (the growth rate of operating income), ROA (return on assets), Return (annual stock return excluding dividends), LEV (assets-liabilities ratio), FirmSize (the log of total assets), SOE (nature of equity ownership), Age (years since a firm is registered), and SA (financial constraints index). Table A1 in Appendix A summarizes the variable definitions.

3.3. Empirical Model

In order to test the impact of environmental tax burden on firms' TFP, we estimate the following ordinary least squares (OLS) regression model:

$$\begin{aligned} TFP_LP_{i,t} = {} & \alpha_0 + \alpha_1 LnEnvtax_{i,t} + \alpha_2 TOP1_{i,t} + \alpha_3 Growth_{i,t} + \alpha_4 ROA_{i,t} + \alpha_5 Return_{i,t} + \alpha_6 LEV_{i,t} \\ & + \alpha_7 FirmSize_{i,t} + \alpha_8 SOE_{i,t} + \alpha_9 Age_{i,t} + \alpha_{10} SA_{i,t} + Year + Industry + \varepsilon_{i,t} \end{aligned} \quad (1)$$

where *TFP_LP* measures total factor productivity, *LnEnvtax* measures environmental tax burden. Control variables include *TOP1*, *Growth*, *ROA*, *Return*, *LEV*, *FirmSize*, *SOE*, *Age*, and *SA*. The α_i represents regression coefficients, and $\varepsilon_{i,t}$ is an error term. We also control industry and year.

To test the mediating effects of Hypothesis 2 and Hypothesis 3, we followed the methodology of Wen and Ye (2014) and constructed a three-step mediation effect model [49]:

$$Mediator_{i,t} = \beta_0 + \beta_1 LnEnvtax_{i,t} + \beta_k Controls_{\ i,t} + Year + Industry + \varepsilon_{i,t} \quad (2)$$

$$TFP_LP_{i,t} = \gamma_0 + \gamma_1 LnEnvtax_{i,t} + \gamma_2 Mediator_{i,t} + \gamma_k Controls_{\ i,t} + Year + Industry + \varepsilon_{i,t} \quad (3)$$

where the Mediator measures mediating variables, i.e., technological innovation and fixed asset investment. Controls indicate control variables, which are the same as in Equation (1). The β_i represents regression coefficients, and $\varepsilon_{i,t}$ is an error term. We also control industry and year.

4. Empirical Results

To examine the correlation between environmental taxes and firms' total factor productivity, we conducted an empirical study. In this section, we present the results of descriptive statistical analysis, correlation coefficient analysis, basic regression analysis, and robustness tests.

4.1. Descriptive Statistics

Table 1 reports the descriptive statistical results of the variables. The mean value of TFP_LP is 10.583, and the standard deviation of 0.817. It indicates that the differences between businesses are relatively minor. The mean value of LnEnvtax is 10.168, maximum value 16.961, minimum value 2.344, and standard deviation 3.030, suggesting the firms' environmental tax burden is significantly different. The results for the control variables are similar to those in prior literature [11–13].

Table 1. Descriptive Statistics for the Variables.

Variables	*n*	Mean	Standard Deviation	Min	Max
TFP_LP	4089	10.583	0.817	8.900	12.693
LnEnvtax	4089	10.168	3.030	2.344	16.961
Inv	4089	0.058	0.050	0.001	0.242
R_D	3893	0.039	0.032	0.000	0.200
TOP1	4089	0.333	0.143	0.087	0.726
Growth	4089	0.153	0.313	−0.454	1.657
ROA	4089	0.051	0.076	−0.279	0.274
Return	4089	0.076	0.475	−0.603	2.060
LEV	4089	0.407	0.184	0.067	0.859
FirmSize	4089	9.739	0.547	8.764	11.261
SOE	4089	0.277	0.447	0	1
Age	4089	12.987	8.330	1	30
SA	4089	−3.933	0.226	−4.534	−3.397
ManCost_ratio	4089	0.797	1.833	−4.058	12.411
LifeCycle	4081	1.789	0.727	1	3

4.2. Correlation Analysis of Variables

Table A2 in Appendix B presents correlations for the variables. In response to prior literature [11–13] shedding light on the effects of the environmental tax burden on firms' TFP, we first analyzed the relationship between the environmental tax burden and firms' TFP, measured by the amount of environmental tax paid by firms. We find that the coefficient of environmental tax burden on TFP is 0.470, which is significantly positive at the 1% level, indicating that environmental tax burden is positively associated with firms' TFP, without considering control variables. Besides, the results indicate that the majority of the bivariate correlations are lower than 0.3. Moreover, we further check for collinearity with Variance Inflation Factors (VIF). The highest VIF is far less than the cut-off points of 10 for all the models. These results indicate that potential multicollinearity could not impact the coefficients of the independent variable.

4.3. Basic Regression Analysis

Table 2 shows the results of the effect of environmental tax burden on firms' TFP. In columns (1) and (2), the influence coefficient of the environmental tax burden on TFP is significantly positive at 1%, meaning that the pressure of environmental protection tax stimulates firms to improve TFP, thus verifying Hypothesis 1a. Columns (3) and (4) are fixed-effect results, and standard errors are clustered at the firm level. The influence coefficients of the environmental tax burden on TFP are significantly positive at 1% and 5%, indicating that the conclusion is robust. Judging from the results, prior literature suggests that market-based regulations, compared to administrative command-and-control regulations, are more effective in achieving the double dividend effect, that is, reducing pollution while increasing production capacity [15]. China's environmental tax burden is positively associated with firms' TFP. This suggests that China's environmental tax system has a certain "double dividend" effect [19–21]. To some extent, this provides some support for the "Porter hypothesis" and the "factor endowment hypothesis".

Table 2. Basic Regression Results.

Dependent Variable	(1) TFP_LP	(2) TFP_LP	(3) TFP_LP	(4) TFP_LP
LnEnvtax	0.134 ***	0.014 ***	0.134 ***	0.014 **
	(35.18)	(4.39)	(18.91)	(2.44)
TOP1		0.217 ***		0.217 **
		(3.93)		(2.30)
Growth		0.225 ***		0.225 ***
		(8.69)		(7.62)
ROA		2.001 ***		2.001 ***
		(17.37)		(10.26)
Return		−0.056 ***		−0.056 ***
		(−3.02)		(−3.75)
LEV		0.505 ***		0.505 ***
		(9.70)		(5.13)
FirmSize		1.022 ***		1.022 ***
		(49.66)		(26.23)
SOE		−0.019		−0.019
		(−0.93)		(−0.50)
Age		0.002 *		0.002
		(1.75)		(0.91)
SA		0.024		0.024
		(0.63)		(0.38)
_cons	9.403 ***	0.149	9.403 ***	0.149
	(84.34)	(0.56)	(56.22)	(0.32)
n	4089	4089	4089	4089
Adjusted R^2	0.290	0.683	0.290	0.683
Year FE	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes
Firm FE			Yes	Yes

Notes: Standard errors are in parentheses. *** $p < 0.01$; ** $p < 0.05$; * $p < 0.10$.

4.4. Robustness Checks

We test the robustness of our findings using several methods. First, we replace the independent variable with the environmental tax rate (Envtax) and find that the Envtax is significantly positively correlated with firms' TFP, with a coefficient of 3.664 at the 1% level. Second, we replace TFP_LP with TFP_OP and find that the impact coefficient of the environmental tax burden on firm TFP_OP is 0.029, significantly positive at the 1% level, indicating a robust conclusion. Third, we use a fixed effects model to control for firm-level factors that may affect both the environmental tax burden and TFP. The results are consistent with previous results; model setting doesn't affect regression results in this study. Fourth, we consider the potential lag effect of the environmental tax burden on firms' TFP and test the model with a one-year lag, but the conclusion remains unchanged. Finally, following Mugerman et al. (2022) [50,51], we examined the effect of the environmental tax burden on firms' TFP with double-clustering at the firm and time levels, and the results are reported in the robustness checks section. All robustness tables are displayed in Appendix C.

5. Further Analysis

The previous results have shown that the environmental tax burden promotes firms' total factor productivity. This section will delve into how the environmental tax burden stimulates total factor productivity and examine whether its impact varies.

5.1. Response Strategy: Fixed Asset Investment or Technological Innovation?

The environmental tax represents a common institutional pressure pushing firms to shift their focus from operational performance to compliance. To address this, firms

typically adopt two strategies. One is an immediate and passive strategy, where they purchase more environmentally friendly production equipment and materials to reduce pollution and tax costs, reflected in increased fixed asset investment. This improves capital quality and TFP. The other is a more sustainable and proactive strategy, where they invest in longer-term technological innovation in response to increased environmental protection expenditures, advancing TFP. Therefore, the question is how do Chinese enterprises choose strategic operational decisions to improve production efficiency?

We represent the fixed asset investment by the ratio of cash paid by enterprises for the purchase and construction of fixed assets, intangible assets, and other long-term assets to the total assets at the end of the year. We represent the level of technological innovation by the ratio of R&D investment to operating revenue. Subsequently, we introduce fixed asset investment and technological innovation as mediating variables into the model to examine the mediating roles of technological innovation and fixed asset investment in the relationship between environmental tax burden and TFP. Table 3 presents the results of the mediating analysis for Hypothesis 2 and Hypothesis 3, elucidating. Columns (1) and (2) illustrate the mediating effect of fixed asset investment. The results indicate that the environmental tax burden positively influences fixed asset investment at the 1% significance level. Both the environmental tax burden and fixed asset investment have a positive impact on TFP, with the coefficient of the environmental tax burden's effect on TFP being 0.013, which is a decrease compared to the baseline regression results. This suggests that fixed asset investment partially mediates the enhancement of total factor productivity by the environmental tax burden. Columns (3) and (4) display the mediating effect of technological innovation. The findings show no significant relationship between the environmental tax burden and technological innovation, indicating that the mediating effect of technological innovation on the impact of the environmental tax burden on enterprise production efficiency has not yet been demonstrated.

Table 3. Mediating Analysis Results.

Dependent Variable	(1) Inv	(2) TFP_lp	(3) R_D	(4) TFP_lp
LnEnvtax	0.001 ***	0.013 ***	−0.002	0.004
	(3.41)	(4.57)	(−1.28)	(1.14)
Inv		1.308 ***		
		(8.08)		
R_D				5.797 ***
				(21.66)
TOP1	0.011 **	0.232 ***	−0.012 ***	0.154 ***
	(2.04)	(4.48)	(−3.74)	(3.16)
Growth	0.006 **	0.233 ***	−0.001	0.205 ***
	(2.20)	(8.07)	(−0.77)	(7.27)
ROA	0.071 ***	2.094 ***	−0.058 ***	1.661 ***
	(6.69)	(15.04)	(−5.78)	(12.98)
Return	−0.000	−0.056 ***	0.001	−0.047 ***
	(−0.08)	(−3.14)	(0.87)	(−2.77)
LEV	0.031 ***	0.545 ***	−0.030 ***	0.359 ***
	(6.13)	(9.42)	(−8.37)	(6.47)
FirmSize	0.005 **	1.028 ***	0.003 ***	1.036 ***
	(2.21)	(47.69)	(2.58)	(50.13)
SOE	−0.009 ***	−0.031	−0.003 ***	−0.028
	(−5.14)	(−1.52)	(−3.13)	(−1.38)
Age	−0.002 ***	−0.000	−0.001 ***	−0.000
	(−14.68)	(−0.15)	(−6.76)	(−0.23)
_cons	0.011	0.165	0.063 ***	0.478 **
	(0.38)	(0.66)	(3.68)	(2.03)

Table 3. *Cont.*

Dependent Variable	(1) Inv	(2) TFP_lp	(3) R_D	(4) TFP_lp
n	4089	4089	3895	3895
adj. R^2	0.175	0.688	0.281	0.728
Year FEs	Yes	Yes	Yes	Yes
Industry FEs	Yes	Yes	Yes	Yes

Notes: Standard errors are in parentheses. *** $p < 0.01$; ** $p < 0.05$.

Unlike previous studies [29–32,52], although we found that the environmental tax burden enhances total factor productivity, upon closer examination of the impact pathway, the influence of China's environmental tax burden on TFP does not occur through technological innovation but is primarily through fixed asset investments. Therefore, this is an important theoretical contribution of the paper, as we are providing evidence that diverges from the "Porter Hypothesis".

5.2. Heterogeneous Effects

We also considered that the impact of environmental tax burden on a firm's total factor productivity may be influenced by various factors, so we conducted a heterogeneous analysis of their relationship under different conditions.

On one hand, the relationship between environmental tax burden and firms' TFP is influenced by explicit firm characteristics such as size, enterprise nature, and lifecycle stage. It is also affected by implicit firm characteristics like financing constraints and information costs. On the other hand, the relationship is also affected by regional characteristics. Therefore, we conducted a relevant heterogeneous analysis of the relationship between the environmental tax burden and the firms' TFP.

5.2.1. The Firm Size and Nature of Ownership Heterogeneous

According to existing research [53,54], firm size is posited to exert a significant influence on fixed asset investment. The firm improves on production efficiency as it grows. Large firms may have more funds and greater flexibility for R&D or fixed asset investment, thereby promoting TFP. Columns (1) and (2) of Table 4 show the relationship between environmental tax burden and TFP differs by firm size. Compared to small firms, large firms show a more significant positive effect of environmental tax burden on TFP.

Table 4. The Firm Size and Nature of Ownership Heterogeneous.

	(1) Large Firms	(2) Small Firms	(3) State-Owned Firms	(4) Non-State-Owned Firms
LnEnvtax	0.020 **	0.011 ***	0.010	0.014 ***
	(2.50)	(3.07)	(1.44)	(3.74)
TOP1	0.184 *	0.251 ***	0.321 ***	0.177 ***
	(1.79)	(4.08)	(3.52)	(2.83)
Growth	0.249 ***	0.207 ***	0.281 ***	0.191 ***
	(5.65)	(5.74)	(4.95)	(5.68)
ROA	1.410 ***	2.118 ***	1.624 ***	2.122 ***
	(4.21)	(14.16)	(6.36)	(13.46)
Return	−0.044	−0.046 **	−0.057	−0.041 **
	(−1.34)	(−2.16)	(−1.55)	(−1.99)
LEV	0.429 ***	0.538 ***	0.484 ***	0.525 ***
	(3.16)	(8.45)	(4.39)	(7.78)
FirmSize	0.980 ***	0.991 ***	1.058 ***	1.003 ***
	(12.92)	(32.03)	(24.01)	(38.17)
SOE	0.024	−0.042 *	0.000	0.000
	(0.64)	(−1.67)	(.)	(.)

Table 4. *Cont.*

	(1) Large Firms	(2) Small Firms	(3) State-Owned Firms	(4) Non-State-Owned Firms
Age	0.001	0.002	0.005 *	−0.000
	(0.43)	(1.01)	(1.92)	(−0.27)
SA	0.110	−0.020	0.066	−0.006
	(0.98)	(−0.47)	(0.80)	(−0.14)
_cons	0.879	0.299	−0.177	0.276
	(0.83)	(0.99)	(−0.29)	(0.96)
n	1024	3065	1133	2956
adj. R^2	0.547	0.482	0.739	0.635
Year Fes	Yes	Yes	Yes	Yes
Industry Fes	Yes	Yes	Yes	Yes
p-value	0.000 ***		0.060 *	

Note: "*p*-value" is used to test the significance of the difference in LnEnvtax coefficient between groups, which is obtained by bootstrap sampling 1000 times. *** $p < 0.01$; ** $p < 0.05$; * $p < 0.10$.

Additionally, compared to state-owned firms, non-state-owned firms typically have a weaker awareness of environmental and social responsibilities, but they exhibit better policy sensitivity [55]. Columns (3) and (4) of Table 4 show the relationship differs by ownership. In non-state-owned firms, the environmental tax burden is significantly positively correlated with TFP at the 1% level. This relationship is insignificant in state-owned firms. Bootstrap *p*-values confirm the significance of these differences: 0.000 and 0.060 for the two groups, respectively, indicating significance at the 1% and 10% levels.

5.2.2. Financing Constraints and Transaction Costs Heterogeneous

Fixed asset spending may be sensitive to the availability of internal finance [55]. We assume that financing constraints are negatively associated with fixed asset investment, thereby reducing the effect of the environmental tax burden on TFP. Based on existing research [56,57], there are various measurement variables for financing constraints, such as the Z-score, SA index, KZ index, WW index, etc. This study adopts the SA index as a substitute for financing constraints, and the results of other measurement variables are not significantly different. The results in Table 5, columns (1) and (2), show that the environmental tax burden significantly promotes TFP more for firms with weaker financing constraints, indicating that it forms a constraint on capital for those with stronger constraints, but those with weaker constraints can easily overcome this.

Table 5. Financing Constraints and Transaction Costs Heterogeneous.

	(1) Strong Financing Constraints	(2) Weak Financing Constraints	(3) High Transaction Costs	(4) Low Transaction Costs
LnEnvtax	0.005	0.025 ***	0.000	0.027 ***
	(1.15)	(5.33)	(0.09)	(5.42)
TOP1	0.202 ***	0.255 ***	0.274 ***	0.135 *
	(2.64)	(3.54)	(3.77)	(1.83)
Growth	0.245 ***	0.191 ***	0.237 ***	0.201 ***
	(5.87)	(5.07)	(4.86)	(5.55)
ROA	2.042 ***	2.110 ***	3.616 ***	1.962 ***
	(11.79)	(10.06)	(9.44)	(12.58)
Return	−0.060 **	−0.049 *	−0.048 *	−0.067 ***
	(−2.39)	(−1.91)	(−1.78)	(−2.79)
LEV	0.501 ***	0.525 ***	0.517 ***	0.540 ***
	(6.43)	(6.17)	(6.33)	(6.47)
FirmSize	0.997 ***	0.995 ***	1.076 ***	0.971 ***
	(28.62)	(32.37)	(35.16)	(30.90)

Table 5. *Cont.*

	(1) Strong Financing Constraints	(2) Weak Financing Constraints	(3) High Transaction Costs	(4) Low Transaction Costs
SOE	0.012	−0.050	0.013	−0.042
	(0.47)	(−1.46)	(0.44)	(−1.45)
Age	0.002	0.005 *	0.005 ***	0.000
	(1.31)	(1.80)	(2.80)	(0.04)
SA	0.080	−0.116	−0.027	0.095 *
	(1.08)	(−1.37)	(−0.56)	(1.85)
_cons	0.707	−0.265	−0.601 *	0.857 **
	(1.55)	(−0.59)	(−1.71)	(2.27)
n	2044	2041	2045	2044
adj. R^2	0.616	0.737	0.675	0.690
Year Fes	Yes	Yes	Yes	Yes
Industry Fes	Yes	Yes	Yes	Yes
p-value	0.000 ***		0.000 ***	

Note: "*p*-value" is used to test the significance of the difference in LnEnvtax coefficient between groups, which is obtained by bootstrap sampling 1000 times. *** $p < 0.01$; ** $p < 0.05$; * $p < 0.10$.

Similarly, fixed assets spending may be sensitive to the transaction costs. Transaction costs are the expenses required to obtain accurate market information, as well as the costs associated with negotiation and ongoing contractual agreements. Although the transaction costs in the investment market are implicit, they may significantly erode the expected excess returns on investment [58]. Referring to existing literature [59,60], we measure transaction costs by the proportion of management expenses to examine the interactive relationship between transaction costs, environmental tax burden, and TFP. Columns (3) and (4) show that the relationship between environmental tax burden and TFP differs under different transaction cost levels. In firms with low transaction costs, the environmental tax burden is significantly positively correlated with TFP at 1%, while not significant in those with high transaction costs. Bootstrap empirical *p* values confirm the significance of these differences, both of which at 0.000, which are significant at the 1% level.

5.2.3. Heterogeneous in Corporate Life Cycle

Based on the literature of Dickinson (2011) and others [61,62], we use the cash flow model method to categorize the sample into growth, mature, and decline stages. Table 6 illustrates that the impact of the environmental tax burden on TFP in the mature stage is less than that in the growth and decline stages. This suggests that stable and profitable firms, having more abundant capital, are not significantly affected by the environmental tax burden on TFP. The bootstrap method confirms the significance of these differences by comparing the significance of the LnEnvtax coefficient differences between growth and non-growth, mature and non-mature, and recession and non-recession stages. The *p*-values are 0.015, 0.000, and 0.000, respectively, indicating significance at the 5%, 1%, and 1% levels.

Table 6. Heterogeneous in Corporate Life Cycle.

	(1) Growth	(2) Mature	(3) Decline
LnEnvtax	0.018 ***	0.007 *	0.022 ***
	(2.97)	(1.65)	(2.63)
TOP1	0.137	0.189 **	0.427 ***
	(1.59)	(2.53)	(3.20)
Growth	0.197 ***	0.272 ***	0.220 ***
	(4.18)	(6.52)	(2.75)
ROA	2.167 ***	2.036 ***	1.718 ***
	(7.66)	(11.69)	(5.46)

Table 6. *Cont.*

	(1) Growth	(2) Mature	(3) Decline
Return	−0.048	−0.054 **	−0.084 *
	(−1.59)	(−2.10)	(−1.86)
LEV	0.568 ***	0.667 ***	0.291 **
	(5.21)	(8.29)	(2.15)
FirmSize	1.017 ***	1.020 ***	1.024 ***
	(27.19)	(33.54)	(18.11)
SOE	0.033	−0.042	−0.050
	(0.84)	(−1.58)	(−0.99)
Age	0.005 **	0.003	−0.009 ***
	(2.25)	(1.40)	(−3.00)
SA	0.067	0.055	−0.211 **
	(1.14)	(1.09)	(−2.14)
_cons	0.248	0.299	−0.642
	(0.58)	(0.80)	(−1.07)
n	1599	1741	737
adj. R^2	0.645	0.741	0.626
Year Fes	Yes	Yes	Yes
Industry Fes	Yes	Yes	Yes
p-value	0.015 **	0.000 ***	0.000 ***

Note: "*p*-value" is used to test the significance of the difference in LnEnvtax coefficient between groups, which is obtained by bootstrap sampling 1000 times. *** $p < 0.01$; ** $p < 0.05$; * $p < 0.10$.

5.2.4. Heterogeneous in Regional

As the prior literature pointed out, locational advantages and governance institutions, as economic factors, will affect the production and investment environment of various regions [22]. Table 7 illustrates the regional differences in the impact of the environmental tax burden on TFP. From the point of regional differences, the east and middle regions have a weak but not strong Porter hypothesis phenomenon while that of the west region is not significant. Our result is similar to the prior literature [52].

Table 7. Heterogeneous in Regional.

	(1) East	(2) Middle	(3) West
LnEnvtax	0.017 ***	0.031 ***	−0.007
	(4.28)	(4.24)	(−0.79)
TOP1	0.197 ***	0.211 *	0.197
	(3.15)	(1.81)	(1.32)
Growth	0.222 ***	0.305 ***	0.137 *
	(6.43)	(4.96)	(1.90)
ROA	2.031 ***	1.721 ***	2.476 ***
	(12.15)	(5.93)	(8.33)
Return	−0.052 **	−0.049	−0.047
	(−2.31)	(−1.28)	(−1.05)
LEV	0.514 ***	0.344 **	0.553 ***
	(7.32)	(2.51)	(3.72)
FirmSize	1.046 ***	0.764 ***	1.134 ***
	(39.90)	(13.07)	(21.45)
SOE	−0.063 **	0.010	0.168 ***
	(−2.34)	(0.26)	(3.35)
Age	0.002	0.019 ***	−0.001
	(1.15)	(5.78)	(−0.29)
SA	−0.017	0.253 ***	0.031
	(−0.39)	(2.87)	(0.31)
_cons	−0.227	3.142 ***	−0.822
	(−0.75)	(4.65)	(−1.14)

Table 7. *Cont.*

	(1) East	(2) Middle	(3) West
n	2798	753	536
adj. R^2	0.678	0.706	0.760
Year FEs	Yes	Yes	Yes
Industry FEs	Yes	Yes	Yes
p-value	0.165	0.000 ***	0.000 ***

Note: "*p*-value" is used to test the significance of the difference in LnEnvtax coefficient between groups, which is obtained by bootstrap sampling 1000 times. *** $p < 0.01$; ** $p < 0.05$; * $p < 0.10$.

6. Discussion and Conclusions

This section presents empirical conclusions and proposes practical suggestions for firms to address environmental taxes based on the main research findings. It also discusses the limitations of the study and suggests future research directions.

6.1. Discussion

This study examined the relationship between environmental tax burden and firms' total factor productivity using panel data from listed companies on the Shanghai and Shenzhen Stock Exchanges from 2018–2022. This study has the following findings.

First, the environmental tax burden positively affects firms' TFP. This indicates that although environmental taxes increase compliance costs for firms, they also enhance their environmental protection efforts and promote green transformation.

Second, the way in which environmental tax pressure affects the production efficiency of firms is through fixed asset investment rather than technological innovation. This implies that environmental regulations force firms to invest in fixed assets to meet emission standards in the short term. We believe that, based on institutional theory, technological innovation is more aligned with proactive strategies and represents a long-term and sustainable environmental strategy. In contrast, fixed asset investment is more of a reactive strategy, serving as a short-term, real-time environmental strategy. Therefore, Chinese firms facing the pressure of environmental taxes have only demonstrated short-term and immediate responses.

Third, when facing the pressure of environmental taxes, firms can enhance production efficiency through fixed asset investment, but such investments require substantial capital. We also discuss the heterogeneous effects on the association between environmental tax burden and firms' total factor productivity. Results show that large-scale firms are more capable of alleviating the increased costs of environmental taxes through measures such as replacing equipment, leading to a more pronounced improvement in firms' TFP. Secondly, non-state-owned firms are more sensitive to the increase in environmental tax costs and will take proactive measures to enhance firms' TFP. In addition, in samples of firms with weaker financing constraints and lower transaction costs, the positive effect of the environmental tax burden on TFP is more significant. This indicates that firms need to choose business strategies according to the specific situation to improve their production efficiency.

6.2. Theoretical Contributions

Our findings contribute to the literature in the following two ways. First, previous literature has primarily discussed the economic consequences of pollution discharge fees and the economic impacts of the "fee-to-tax" event. This study uses the amount of environmental tax payment as a proxy for firms' environmental tax burden and examines the micro-effects of environmental tax pressure on firms. This study primarily focuses on the impact of the 'quantity' of environmental taxes on corporate production efficiency. This work supplements the literature on environmental tax reform effects and introduces the concept of environmental tax burden and a measurement method.

Second, using empirical data from China, this study shows that environmental tax burden enhances total factor productivity primarily through reactive business strategies,

such as fixed asset investments, rather than proactive business strategies, like technological innovation. This finding enriches the literature on the relationship between corporate environmental behavior and production efficiency, providing evidence outside the "Porter hypothesis". This study complements the literature on the effectiveness of environmental tax reforms.

6.3. Managerial Implications

Practically, our findings provide managerial implications for practitioners and policymakers.

China's implementation of the environmental tax in 2018 was a significant policy decision in achieving the 2030 carbon peak and 2060 carbon neutrality goals. Our findings provide important policy implications for policymakers. Firstly, environmental taxes can effectively enhance firms' total factor productivity, so policymakers should actively promote the implementation of such taxation. Based on thorough justification, the level of environmental tax collection could be appropriately increased. Secondly, the intermediary mechanism through which environmental taxes affect firms' total factor productivity is fixed asset investment. From this perspective, policymakers should focus on providing convenience for the renewal of business assets. Thirdly, policymakers should also consider that during the asset replacement process, certain small and medium-sized enterprises (SMEs), private enterprises, and enterprises facing financing difficulties may face excessive tax pressure due to the inability to complete asset replacement smoothly. Countries should actively consider providing a more convenient policy environment to facilitate financing for such entities. Finally, the research findings are also beneficial for policymakers to refine the environmental tax system, stimulate corporate innovation potential, and promote economic growth and emission reduction.

Our findings also provide important managerial implications for enterprise leaders. When facing environmental tax burdens, firms must respond with either proactive or reactive strategies in order to maintain sustainable development. Besides, firms can seize this opportunity to update their fixed assets through the imposition of environmental taxes, thereby achieving both economic and social benefits. In practice, it helps firms to identify the best strategies for coping with the environmental tax burden, thereby assisting them in achieving the dual goals of energy conservation and stable performance.

6.4. Limitations and Future Research

This paper has the following limitations. First, according to institutional theory, we categorize business strategies into proactive strategies and reactive strategies to cope with the environmental tax burden. Among them, proactive strategies such as technological innovation require a longer period of development. However, the scope of this article covers the period from 2018 to 2022, which may not be long enough. In the future, extending the sample period could allow for continued observation of innovative strategies. Second, this study does not analyze the impact of different fixed asset investments and types of innovation on the relationship between environmental tax burdens and TFP. Future research can further deepen the study and analyze more detailed scenarios in which environmental tax burdens enhance TFP.

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Appendix A

Table A1. Variable definitions.

Variables	Description
TFP_OP	Calculated following Olley and Pakes (1996)
TFP_LP	Calculated following Levinsohn and Petrin (2003)
LnEnvtax	The natural log of the amount of environmental tax payable at the end of year t.
Envtax	The ratio of the amount of environmental tax payable for year t to the total tax payable at the end of year t.
Inv	The ratio of cash paid by a firm for the acquisition and construction of fixed assets, intangible assets, and other long-term assets to total assets at the end of year t.
R_D	The ratio of R&D investment divided by operating revenue at the end of year t.
TOP1	The percentage of shares held by the largest shareholder at the end of year t.
Growth	The ratio of the difference between the total operating income of the year t and the total operating income of year t − 1 divided by the total operating income of the year t − 1.
ROA	Return on assets, defined as net income for year t divided by total assets at the end of year t.
Return	The annual return on individual stocks excluding dividends at the end of year t.
LEV	Total liabilities divided by total assets, at the end of year t.
FirmSize	The natural log of total assets as of the end of year t.
SOE	A dummy variable that equals 1 if the ultimate controlling shareholder of the company is the state, and 0 otherwise.
Age	Years since a firm is registered
SA	The SA index calculated according to the formula by Hadlock and Pierce (2010), the larger the absolute value of the SA index, the more severe the financing constraints of the company are.
ManCost_ratio	The ratio of management expenses at the end of year t to total profit.
LifeCycle	Using the cash flow model method (Dickinson, 2011), the sample is categorized into three stages: the growth phase, the mature phase, and the decline phase, with corresponding values of 1, 2, and 3, respectively.

Appendix B

Table A2. Correlations for the Variables.

	TFP_LP	LnEnvtax	TOP1	Growth	ROA	Return	LEV	FirmSize	SOE	Age
TFP_LP	1									
LnEnvtax	0.470 ***	1								
TOP1	0.158 ***	0.144 ***	1							
Growth	0.196 ***	0.045 ***	0.024	1						
ROA	0.217 ***	0.049 ***	0.159 ***	0.295 ***	1					
Return	0.071 ***	0.016	−0.006	0.250 ***	0.209 ***	1				
LEV	0.403 ***	0.304 ***	0.013	0.054 ***	−0.342 ***	0.015	1			
FirmSize	0.767 ***	0.600 ***	0.171 ***	0.089 ***	0.060 ***	0.050 ***	0.500 ***	1		
SOE	0.247 ***	0.352 ***	0.230 ***	−0.035 **	−0.048 ***	−0.013	0.210 ***	0.382 ***	1	
Age	0.339 ***	0.415 ***	−0.005	−0.086 ***	−0.093 ***	0.020	0.279 ***	0.468 ***	0.508 ***	1

Note: The table presents a matrix of Pearson correlation coefficients. *** $p < 0.01$; ** $p < 0.05$.

Appendix C

Table A3. Robustness Check for Replacing Independent Variables.

Dependent Variable	(1) TFP_LP	(2) TFP_LP	(3) TFP_LP	(4) TFP_LP
Envtax	3.664 ***	1.372 ***	3.664 ***	1.372 *
	(6.07)	(3.02)	(3.31)	(1.73)

Table A3. *Cont.*

Dependent Variable	(1) TFP_LP	(2) TFP_LP	(3) TFP_LP	(4) TFP_LP
TOP1		0.467 ***		0.467 ***
		(6.54)		(3.52)
Growth		0.261 ***		0.261 ***
		(6.87)		(6.98)
ROA		3.750 ***		3.750 ***
		(21.69)		(15.28)
Return		−0.087 ***		−0.087 ***
		(−3.48)		(−4.03)
LEV		1.830 ***		1.830 ***
		(26.67)		(15.18)
SOE		0.081 ***		0.081
		(2.90)		(1.59)
Age		0.032 ***		0.032 ***
		(19.53)		(10.45)
SA		0.621 ***		0.621 ***
		(12.88)		(6.92)
_cons	10.550 ***	11.449 ***	10.843 ***	11.656 ***
	(817.55)	(58.99)	(59.74)	(29.26)
n	4089	4089	4089	4089
adj. R^2	0.084	0.441	0.084	0.441
Year FE	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes
Firm FE			Yes	Yes

Notes: Standard errors are in parentheses. *** $p < 0.01$; * $p < 0.10$.

Table A4. Robustness Check for Replacing Dependent Variables.

	(1) TFP_OP	(2) TFP_OP	(3) TFP_OP	(4) TFP_OP
LnEnvtax	0.093 ***	0.029 ***	0.093 ***	0.029 ***
	(29.57)	(8.53)	(16.41)	(4.93)
TOP1		0.124 **		0.124
		(2.15)		(1.18)
Growth		0.274 ***		0.274 ***
		(8.63)		(7.94)
ROA		1.594 ***		1.594 ***
		(12.01)		(8.54)
Return		−0.042 **		−0.042 **
		(−2.13)		(−2.55)
LEV		0.417 ***		0.417 ***
		(7.00)		(4.07)
FirmSize		0.520 ***		0.520 ***
		(23.65)		(13.22)
SOE		−0.076 ***		−0.076 *
		(−3.47)		(−1.87)
Age		0.003 *		0.003
		(1.83)		(1.00)
SA		0.021		0.021
		(0.53)		(0.29)
_cons	4.560 ***	−0.113	4.550 ***	−0.237
	(138.56)	(−0.42)	(40.35)	(−0.47)
n	4089	4089	4089	4089
adj. R^2	0.239	0.448	0.240	0.449
Year FE	Yes	Yes	Yes	Yes

Table A4. *Cont.*

	(1) TFP_OP	(2) TFP_OP	(3) TFP_OP	(4) TFP_OP
Industry FE	Yes	Yes	Yes	Yes
Firm FE			Yes	Yes

Notes: Standard errors are in parentheses. *** $p < 0.01$; ** $p < 0.05$; * $p < 0.10$.

Table A5. Robustness Check of Fixed Effects Model.

	(1) TFP_LP	(2) TFP_LP	(3) TFP_LP	(4) TFP_LP
LnEnvtax	0.134 ***	0.014 ***	0.134 ***	0.014 **
	(34.31)	(4.13)	(18.91)	(2.44)
TOP1		0.217 ***		0.217 **
		(4.14)		(2.30)
Growth		0.225 ***		0.225 ***
		(7.85)		(7.62)
ROA		2.001 ***		2.001 ***
		(14.50)		(10.26)
Return		−0.056 ***		−0.056 ***
		(−3.09)		(−3.75)
LEV		0.505 ***		0.505 ***
		(8.75)		(5.13)
FirmSize		1.022 ***		1.022 ***
		(46.88)		(26.24)
SOE		−0.019		−0.019
		(−0.92)		(−0.50)
Age		0.002 *		0.002
		(1.67)		(0.91)
SA		0.024		0.024
		(0.68)		(0.38)
_cons	9.224 ***	0.151	9.224 ***	0.151
	(225.94)	(0.59)	(128.52)	(0.33)
n	4089	4089	4089	4089
adj. R^2	0.289	0.683	0.289	0.683
Year FE	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes
Firm FE			Yes	Yes

Notes: Standard errors are in parentheses. *** $p < 0.01$; ** $p < 0.05$; * $p < 0.10$.

Table A6. Robustness Check of one-year-lagged Variables.

	(1) TFP_LP	(2) TFP_LP	(3) TFP_LP	(4) TFP_LP
L.LnEnvtax	0.140 ***	0.016 ***	0.140 ***	0.016 **
	(29.84)	(3.70)	(17.68)	(2.38)
L.TOP1		0.282 ***		0.282 **
		(4.15)		(2.57)
L.Growth		0.254 ***		0.254 ***
		(6.52)		(6.36)
L.ROA		1.516 ***		1.516 ***
		(9.09)		(7.04)
L.Return		0.003		0.003
		(0.12)		(0.12)
L.LEV		0.420 ***		0.420 ***
		(5.53)		(3.62)
L.FirmSize		1.026 ***		1.026 ***
		(35.59)		(22.36)

Table A6. *Cont.*

L.SOE		−0.007		−0.007
		(−0.27)		(−0.16)
L.Age		0.002		0.002
		(0.95)		(0.57)
	(1)	**(2)**	**(3)**	**(4)**
	TFP_LP	**TFP_LP**	**TFP_LP**	**TFP_LP**
L.SA		0.084 *		0.084
		(1.77)		(1.10)
_cons	9.187 ***	0.389	9.187 ***	0.389
	(181.63)	(1.12)	(110.35)	(0.71)
n	2730	2730	2730	2730
adj. R^2	0.298	0.658	0.298	0.658
Year FE	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes
Firm FE			Yes	Yes

Notes: Standard errors are in parentheses. *** $p < 0.01$; ** $p < 0.05$; * $p < 0.10$.

Table A7. Robustness check of double-clustering at the firm and time levels.

	(1)	**(2)**	**(3)**	**(4)**
	TFP_LP	**TFP_LP**	**TFP_LP**	**TFP_LP**
LnEnvtax	0.134 ***	0.014 ***	0.132 ***	0.014 ***
	(34.30)	(4.13)	(20.12)	(2.63)
TOP1		0.217 ***		0.215 ***
		(4.14)		(2.59)
Growth		0.225 ***		0.220 ***
		(7.85)		(10.36)
ROA		2.001 ***		1.986 ***
		(14.50)		(7.84)
Return		−0.056 ***		−0.046 ***
		(−3.09)		(−5.49)
LEV		0.505 ***		0.501 ***
		(8.75)		(3.80)
FirmSize		1.022 ***		1.027 ***
		(46.87)		(32.48)
SOE		−0.019		−0.017
		(−0.92)		(−0.54)
Age		0.002 *		0.002
		(1.67)		(0.91)
SA		0.024		0.011
		(0.68)		(0.19)
_cons	9.403 ***	0.149	9.498 ***	0.085
	(96.50)	(0.56)	(58.00)	(0.20)
n	4089	4089	4089	4089
adj. R^2	0.290	0.683	0.285	0.683
Industry	Control	Control	Control	Control
Year	Control	Control	Cluster	Cluster
Firm			Cluster	Cluster

Notes: Standard errors are in parentheses. *** $p < 0.01$; * $p < 0.10$.

References

1. Porter, M.E.; Linde, C. Toward a new conception of the environment-competitiveness relationship. *J. Econ. Perspect.* **1995**, *9*, 97–118. [CrossRef]
2. Ambec, S.; Barla, P. A theoretical foundation of the Porter hypothesis. *Econ. Lett.* **2002**, *75*, 355–360. [CrossRef]
3. Gray, W.B. The cost of regulation: OSHA, EPA and the productivity slowdown. *Am. Econ. Rev.* **1987**, *77*, 998–1006.
4. Jaffe, A.B.; Peterson, S.R.; Portney, P.R.; Stavins, R.N. Environmental Regulation and the Competitiveness of, U.S. Manufacturing: What Does the Evidence Tell Us. *J. Econ. Lit.* **1995**, *33*, 132–163.

5. Barbera, A.J.; McConnell, V.D. The impact of environmental regulations on industry productivity: Direct and indirect effects. *J. Environ. Econ. Manag.* **1990**, *18*, 50–65. [CrossRef]
6. Telle, K.; Larsson, J. Do Environmental Regulations Hamper Productivity Growth? How accounting for Improvements of Plants' Environmental Performance can Change the Conclusion. *Ecol. Econ.* **2007**, *61*, 438–445. [CrossRef]
7. He, Y.; Zhu, X.; Zheng, H. The influence of environmental protection tax law on total factor productivity: Evidence from listed firms in China. *Energy Econ.* **2022**, *113*, 106248. [CrossRef]
8. Hu, H.; Dong, W.; Zhou, Q. A comparative study on the environmental and economic effects of a resource tax and carbon tax in China: Analysis based on the computable general equilibrium model. *Energy Policy* **2021**, *156*, 112460. [CrossRef]
9. Ji, S.; Jiang, F.; Li, J.; Wang, Y.; Zhang, W. Assessment of the performances of pollutant discharge fee in China. *Ecol. Indic.* **2021**, *125*, 107468. [CrossRef]
10. Liu, G.; Yang, Z.; Zhang, F.; Zhang, N. Environmental tax reform and environmental investment: A quasi-natural experiment based on China's Environmental Protection Tax Law. *Energy Econ.* **2022**, *109*, 106000. [CrossRef]
11. Jin, Y.; Gu, J.; Zeng, H. Will the Environmental Protection Fee Reform Affect Enterprise Performance? *J. Account. Res.* **2020**, *5*, 117–133. (In Chinese)
12. Mi, F.; Zhang, Z. Does the Environmental taxes Promote Corporate Innovation Results? An Empirical Study Based on the Data of Chinese Corporate Patents. *J. Harbin Univ. Commer. (Soc. Sci. Ed.)* **2020**, *6*, 80–90. (In Chinese)
13. Yu, L.; Zhang, W.; Bai, X. Does the Environmental Protection Fee Reform to Tax Promote the Green Transformation of Pollution-intensive Enterprises? Evidence from the Quasi-natural Experiment of the Implementation of the Environmental Protection Tax Law. *J. Popul. Resour. Environ.* **2021**, *31*, 109–118. (In Chinese)
14. Evans, C. Taxation compliance and administrative costs: An overview. In *Tax Compliance Costs for Companies in an Enlarged European Community*; Lang, M., Obermair, C., Schuch, J., Staringer, C., Weninger, P., Eds.; Linde Verlag, Vienna and Kluwer Law International: London, UK, 2008; pp. 447–468.
15. Steinbrunner, P.R. Boon or bane? On productivity and environmental regulation. *Environ. Econ. Policy Stud.* **2022**, *24*, 365–396. [CrossRef]
16. Blackman, A. Colombia's discharge fee program: Incentives for polluters or regulators? *J. Environ. Manag.* **2009**, *90*, 101–119. [CrossRef]
17. Bell, R.G.; Russell, C. Environmental policy for developing countries. *Issues Sci. Technol.* **2002**, *18*, 63–70.
18. Maung, M.; Wilson, C.; Tang, X. Political connections and industrial pollution: Evidence based on state ownership and environmental levies in China. *J. Bus. Ethics* **2016**, *138*, 649–659. [CrossRef]
19. Gimenez, E.L.; Rodriguez, M. Reevaluating the first and the second dividends of environmental tax reforms. *Energy Policy* **2010**, *38*, 6654–6661. [CrossRef]
20. Ciaschini, M.; Pretaroli, R.; Severini, F.; Socci, C. Regional double dividend from environmental tax reform: An application for the Italian economy. *Res. Econ.* **2012**, *66*, 273–283. [CrossRef]
21. Wesseh, P.K., Jr.; Lin, B. Environmental policy and "double dividend" in a transitional economy. *Energy Policy* **2019**, *134*, 110947. [CrossRef]
22. Bashir, M.F.; Ma, B.; Shahzad, L.; Liu, B.; Ruan, Q. China's quest for economic dominance and energy consumption: Can Asian economies provide natural resources for the success of One Belt One Road? *Manag. Decis. Econ.* **2021**, *42*, 570–587. [CrossRef]
23. Ziolo, M.; Bak, I.; Cheba, K. Environmental taxes—How public policy makers can use them in the decision-making process? *Procedia Comput. Sci.* **2019**, *159*, 2216–2223. [CrossRef]
24. Geng, Y.; Liu, W.; Li, K.; Chen, H. Environmental regulation and corporate tax avoidance: A quasi-natural experiment based on the eleventh Five-Year Plan in China. *Energy Econ.* **2021**, *99*, 105312. [CrossRef]
25. Tang, H.; Liu, J.; Wu, J. The impact of command-and-control environmental regulation on enterprise total factor productivity: A quasi-natural experiment based on China's "Two Control Zone" policy. *J. Clean. Prod.* **2020**, *254*, 120011. [CrossRef]
26. Cai, W.; Ye, P. How does environmental regulation influence enterprises' total factor productivity? A quasi-natural experiment based on China's new environmental protection law. *J. Clean. Prod.* **2020**, *276*, 124105. [CrossRef]
27. Yamazaki, A. Environmental taxes and productivity: Lessons from Canadian manufacturing. *J. Public Econ.* **2022**, *205*, 104560. [CrossRef]
28. Commins, N.; Lyons, S.; Schiffbauer, M.; Tol, R.S. Climate policy & corporate behavior. *Energy J.* **2011**, *32*, 51–68.
29. Peng, J.; Xie, R.; Ma, C.; Fu, Y. Market-based environmental regulation and total factor productivity: Evidence from Chinese enterprises. *Econ. Model.* **2021**, *95*, 394–407. [CrossRef]
30. Wu, Q.; Wang, Y. How does carbon emission price stimulate enterprises' total factor productivity? Insights from China's emission trading scheme pilots. *Energy Econ.* **2022**, *109*, 105990. [CrossRef]
31. Song, M.; Peng, L.; Shang, Y.; Zhao, X. Green technology progress and total factor productivity of resource-based enterprises: A perspective of technical compensation of environmental regulation. *Technol. Forecast. Soc. Chang.* **2022**, *174*, 121276. [CrossRef]
32. Copeland, B.R.; Taylor, M.S. Trade, growth, and the environment. *J. Econ. Lit.* **2004**, *42*, 7–71. [CrossRef] [PubMed]
33. Xu, F.; Liu, X.; Liu, Q.; Zhu, X.; Zhou, D. Environmental investment growth (EIG) and corporate cost stickiness in China: Substantive or symbolic management? *Sustain. Account. Manag. Policy J.* **2024**, *15*, 148–170. [CrossRef]
34. Wang, J.; Wang, K.; Shi, X.; Wei, Y.M. Spatial heterogeneity and driving forces of environmental productivity growth in China: Would it help to switch pollutant discharge fees to environmental taxes? *J. Clean. Prod.* **2019**, *223*, 36–44. [CrossRef]

35. Kochhar, R.; David, P. Institutional investors and firm innovation: A test of competing hypotheses. *Strateg. Manag. J.* **1996**, *17*, 73–84. [CrossRef]
36. Tina Dacin, M.; Goodstein, J.; Richard Scott, W. Institutional theory and institutional change: Introduction to the special research forum. *Acad. Manag. J.* **2002**, *45*, 45–56. [CrossRef]
37. Scott, W.R. Institutional theory: Contributing to a theoretical research program. *Great Minds Manag. Process Theory Dev.* **2005**, *37*, 460–484.
38. Ji, H.; Xu, G.; Zhou, Y.; Miao, Z. The Impact of Corporate Social Responsibility on Firms' Innovation in China: The Role of Institutional Support. *Sustainability* **2019**, *11*, 6369. [CrossRef]
39. Zilber, T.B. The relevance of institutional theory for the study of organizational culture. *J. Manag. Inq.* **2012**, *21*, 88–93. [CrossRef]
40. Bruton, G.D.; Ahlstrom, D.; Li, H. Institutional Theory and Entrepreneurship: Where Are We Now and Where Do We Need to Move in the Future? *Entrep. Theory Pract.* **2010**, *34*, 421–440. [CrossRef]
41. Zucker, L.G. Institutional theories of organization. *Annu. Rev. Sociol.* **1987**, *13*, 443–464. [CrossRef]
42. Young, M.N.; Tsai, T.; Wang, X.; Liu, S.; Ahlstrom, D. Strategy in Emerging Economies and the Theory of the Firm. *Asia Pac. J. Manag.* **2014**, *31*, 331–354. [CrossRef]
43. Zhao, M. Conducting R&D in Countries with Weak Intellectual Property Rights Protection. *Manag. Sci.* **2006**, *52*, 1185–1199.
44. Carfora, A.; Pansini, R.V.; Scandurra, G. The Role of Environmental Taxes and Public Policies in Supporting RES Investments in EU Countries: Barriers and Mimicking Effects. *Energy Policy* **2021**, *149*, 112044. [CrossRef]
45. Xia, J.; Ma, X.; Lu, J.W.; Yiu, D.W. Outward foreign direct investment by emerging market firms: A resource dependence logic. *Strateg. Manag. J.* **2014**, *35*, 1343–1363. [CrossRef]
46. Quan, X.; Ke, Y.; Qian, Y.; Zhang, Y. CEO foreign experience and green innovation: Evidence from China. *J. Bus. Ethics* **2021**, *182*, 535–557. [CrossRef]
47. Olley, S.; Pakes, A. The Dynamics of Productivity in the Telecommunications Industry. *Econometrica* **1996**, *64*, 1263–1298. [CrossRef]
48. Levinsohn, J.; Petrin, A. Estimating Production Functions using Inputs to Control for Unobservables. *Rev. Econ. Stud.* **2003**, *70*, 317–341. [CrossRef]
49. Wen, Z.; Ye, B. Mediation Effect Analysis: Methods and Model Development. *Adv. Psychol. Sci.* **2014**, *22*, 731–745. (In Chinese) [CrossRef]
50. Mugerman, Y.; Steinberg, N.; Wiener, Z. The exclamation mark of Cain: Risk salience and mutual fund flows. *J. Bank. Financ.* **2022**, *134*, 235–253. [CrossRef]
51. Yang, G.; Jiang, A. The 'Protective Shield' for Bond Investors or the 'Domino' of Debt Default—An Analysis of the Cross-Default Provision in Bonds. *China Ind. Econ.* **2022**, *5*, 140–158. (In Chinese)
52. Zhao, X.; Sun, B. The influence of Chinese environmental regulation on corporation innovation and competitiveness. *J. Clean. Prod.* **2016**, *112*, 1528–1536. [CrossRef]
53. Kadapakkam, P.R.; Kumar, P.C.; Riddick, L.A. The impact of cash flows and firm size on investment: The international evidence. *J. Bank. Financ.* **1998**, *22*, 293–320. [CrossRef]
54. Chi, C.K.; Choi, K.J. The impact of firm size on dynamic incentives and investment. *RAND J. Econ.* **2017**, *48*, 147–177. [CrossRef]
55. Garde-Sanchez, R.; López-Pérez, M.V.; López-Hernández, A.M. Current trends in research on social responsibility in state-owned enterprises: A review of the literature from 2000 to 2017. *Sustainability* **2018**, *10*, 2403. [CrossRef]
56. Costa, H.; Demmou, L.; Franco, G.; Lamp, S. The role of financing constraints and environmental policy on green investment. *Econ. Lett.* **2024**, *239*, 111741. [CrossRef]
57. Hadlock, C.J.; Pierce, J.R. New Evidence on Measuring Financial Constraints: Moving Beyond the KZ Index. *Rev. Financ. Stud.* **2010**, *23*, 1909–1940. [CrossRef]
58. Abinzano, I.; Gonzalez-Urteaga, A.; Muga, L.; Sanchez, S. Performance of Default-risk Measures: The Sample Matters. *J. Bank. Financ.* **2020**, *120*, 105959. [CrossRef]
59. Li, F.; Chow, T.M.; Pickard, A.; Garg, Y. Transaction costs of factor-investing strategies. *Financ. Anal. J.* **2019**, *75*, 62–78. [CrossRef]
60. Wu, H.; Wu, S.; Chen, H. Urban Civilization, Transaction Costs, and the "Fourth Source of Profit" for Enterprises—Evidence from the Propensity Score Matching Difference-in-Differences Method of National Civilized Cities and Privately-Listed Companies. *China Ind. Econ.* **2015**, *7*, 114–129. (In Chinese)
61. Dickinson, V. Cash Flow Patterns as a Proxy for Firm Life Cycle. *Account. Rev.* **2011**, *86*, 1969–1994. [CrossRef]
62. Liu, S.; Lin, Z.; Leng, Z. Do tax incentives improve the level of corporate innovation?—A test based on firm life cycle theory. *Econ. Res.* **2020**, *55*, 105–121. (In Chinese)

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Two-Way Perspectives and Attitudes about Environmentally Friendly Agro-Food Production and Consumption: An Empirical Survey for Greece

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Abstract: Relying on pesticides to safeguard crops has led to pest resistance and detrimental environmental and health consequences. Many integrated pest management programs focus on producers' decision-making processes when selecting and implementing pest management interventions. Alternative approaches such as integrated pest management and biological control have been implemented to address these challenges, with Greece as the research area. A quantitative study was oriented to consumers and producers to investigate their views on the effectiveness of pesticides, aiming to assess whether these perspectives influence their attitudes toward adopting pest management practices. Primary data were gathered through structured questionnaires to consumers and producer associations (focusing on tomatoes, olives, and citrus fruits) and analyzed through multivariate methods. The findings unveiled varying preferences and concerns regarding plant protection tools, with considerations such as product effectiveness, method awareness, and sustainability. Specifically, the study revealed aspects like the popularity and demand for specific plant protection tools, the knowledge of these experts about products and pest control methods, and their stance on sustainable agriculture and environmental aspects of pest control.

Keywords: consumer attitudes; producer perceptions; environmentally friendly pesticides; innovative tools; factor analysis; logistic regression

1. Introduction

Pesticides have been relied upon by farmers since the beginning of time to protect their crops from a wide range of dangers, such as diseases, insects, weeds, and nematodes [1]. The primary purpose of these products was to enhance the quality of the food that was produced and to secure yield consistency. Although pesticides may be used in various practical ways, the overuse of the drastic substances and careless application have led to severe problems for humans and the environment [2]. Pesticide resistance, pollution, and health hazards for both farmers and consumers are expected results [3]. Table 1 illustrates the most important chemical pesticides and their human health impacts.

To successfully overcome the issues encountered in the agricultural sector, it is essential to discover novel solutions considering the most significant socioeconomic repercussions. Significant health concerns have been raised because of the extensive and continued use of chemical crop protection agents, which adds to the environmental duties that are already present. This is especially true in circumstances when production could be more efficiently managed. The harsh weather conditions in several countries have significantly increased

the pesticides farmers use in their agricultural operations. Agricultural goods become more dangerous due to this, highlighting the need to teach farmers the appropriate use of pesticides [4].

Table 1. Chemical pesticides and impact on human health.

Organophosphorus Pesticides: Glyphosate, malathion, parathion, and dimethoate	Cardiovascular diseases Negative effects on the male reproductive system and the nervous system Dementia Increased risk for non-Hodgkin's lymphoma neurological problems occur in children in case of prenatal exposure to organophosphates
Carbamate Pesticides: aldicarb, carbofuran, and ziram	Neurobehavioral effects, increased risk for dementia, non-Hodgkin's lymphoma
Triazines: Atrazine, simazine, and ametryn	Breast cancer incidence Oxidative stress, cytotoxicity, and dopaminergic effects

Source: https://www.eea.europa.eu/publications/how-pesticides-impact-human-health; accessed on 27 June 2024.

Within the regime structured by Agenda 2030 and specialized for the EU region, a set of good practices was introduced to reduce the use of fertilizers and pesticides in agricultural systems based on the documentation of the impact of these substances on human health and the environment [5]. The existing solutions available are not only in line with the objectives of the Green Deal and the Common Agricultural Policy, but also effective. Thus, the main issue currently involves enhancing the adoption rate of environmentally friendly low-risk pesticides as defined by the current European Union (EU) Plant Protection Commission Regulation EC No 1107/2009 (PPP reg). These involve pesticides from a biological origin, but this does not mean that all biological pesticides have a low-risk profile [6]. Those are suggested within the broader effort realized via integrated pest management (IPM), biological control, and crops resistant to pests. However, obstacles still limit the extended use of these technologies, though they have the potential to bring benefits. When it comes to cost and producer acceptability, these obstacles are most readily apparent in the market landscape, as areas that have traditional agricultural systems may have a tough time adopting this system due to the significant financial investment and the training of farmers necessary for effective implementation [7].

The degree to which IPM strategies are seen and accepted by producers is affected by various factors including the temperature, the topography, and crop species. Compared to larger-scale producers, small-scale producers often experience a greater degree of resistance to change due to their lack of the resources and technical expertise necessary to create their goods [8,9]. The increasing awareness of customers and their preference for organic food, which in turn have affected agricultural practices, have led to an increase in the need for crop protection systems that are environmentally friendly. This is a fact documented especially in the EU by the economic growth of the organic market within the time period 2000–2018, as illustrated in Figure 1.

Evidently, the expansion of retail sales in the organic market unveils the positive consumer attitude towards organic products, oriented by the perception of the environmental benefits of organic production, the consumers' demand for healthier food, as well as by the growing concern that excessive exposure to pesticides and the overuse of antibiotics have negative effects on health conditions.

The change in consumer demand encourages farmers to adopt a comprehensive strategy that considers consumer behavior, technical improvements, and socioeconomic issues to solve the difficulties brought about by pesticide use [7]. There is a pressing need for further efforts to raise awareness about the health and environmental risks of pesticide usage.

Based on the factors mentioned above, this research seeks to raise public awareness and evaluate the socioeconomic impacts of environmentally friendly production and consumption. The aim was to shed light on the market, individual, and demographic factors as

determinants for the production and consumption of environmentally friendly agricultural products. The research involves consumers and producers in Greece (focusing on tomatoes, olives, and citrus fruits) with a central objective to explore the factors determining consumers' perceptions about environmentally friendly food and producers' decisions to adopt environmentally friendly production methods. The novelty of the present study lies in its comprehensive exploration of the attitudes and perspectives of both producers and consumers towards the adoption of novel pesticide products, particularly in the context of tomatoes, olives, and citrus fruits. While the detrimental effects of pesticide reliance are well documented, this study focuses on low-risk pesticides of biological origin as an alternative to chemical pesticides in agriculture, and more specifically on the decision-making processes of producers and the factors affecting their choices in adopting innovative pest management interventions.

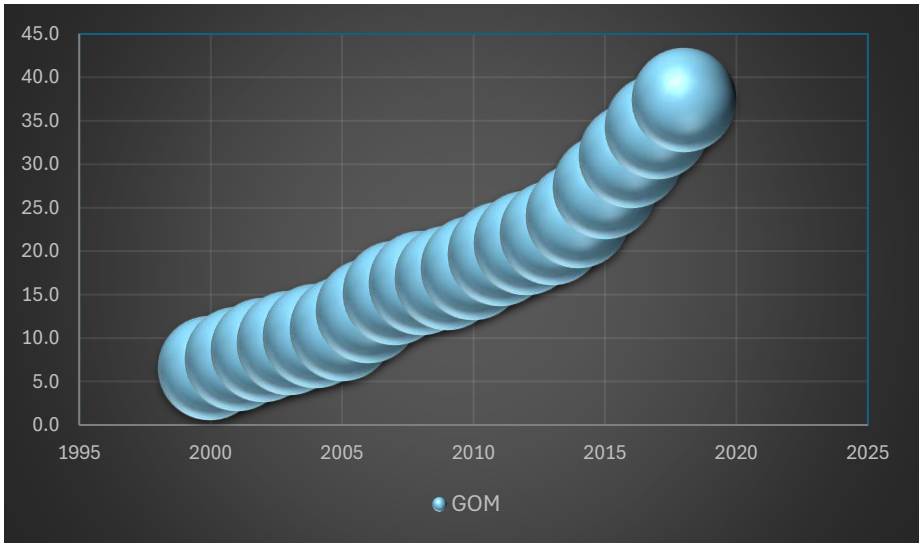


Figure 1. Growth of organic retail sales in the European Union, 2000–2018. Source: FiBL-AMI surveys 2004–2020 and Organic Data Network Surveys 2013–2015.

Accordingly, the remainder of the paper includes the theoretical background of consumers' and producers' perceptions in the second section and the materials and methods employed in the third. The presentation of the results follows in the fourth section, the fifth section discusses the study's results, and the sixth concludes.

2. Theoretical Background

2.1. Consumer Perceptions

The extensive and irresponsible use of pesticides has caused significant worry among farmers and the public over the effects of these chemicals on human health [10]. Consumers' expenses on plant protection tools are subsequently affected. The use of pesticides, the impact on the environment, the safety of products, the safety of food, and the general socioeconomic ramifications of agricultural production are issues on which consumers' views have become increasingly sensitive over the last several decades [11,12].

As a direct consequence of this enhanced knowledge, a shift in consumers' preferences for items that adhere to specific criteria has been detected, most notably those related to standards that pertain to the use of pesticides. In modern societies, a rise in the demand for organic foods has been recorded, produced with reduced or no pesticide use. Grunert [13] identifies various factors influencing consumers' choice of environmentally friendly foods and preferences. The relationship between food safety, quality, and consumer perception is a crucial indicator of how much consumers value products that fulfill these criteria. Ref. [14] argued that when making decisions about their purchases, consumers in developing nations place a high value on aesthetics, health, and environmental

awareness. Ref. [15] revealed an emotional connection to nutrition and nature. In contrast, Refs. [16,17] argued that consumers' decisions are affected by labeling that notifies the health impact of food products on consumers since today's food trends mainly stem from consumers' fears arising from a series of health concerns, as well as the ecological footprint that describes the environmental impact of the food supply function, while organic products are alluring for certain types of consumers. Moreover, the purchasing decision process in Northern European countries is gradually affected more and more by quality indices, including Protected Designation of Origin (PDO), Protected Geographical Indication (PGI), and Traditional Specialty Guaranteed (TSG) [18].

In a nutshell, the contemporary agriculture sector is beset by many problems that need novel approaches. It is important to note that many concerns relate to one another, in addition to those that pertain to health and the environment. The lack of access to food, the preservation of water resources, and the preservation of the environment are all challenges that have to be tackled [19]. The widespread and, in some cases, poorly controlled use of chemical pesticides is a significant cause for worry since it poses considerable risks to the health of consumers as well as to the environment [20,21].

Consumers have diverse perceptions of food-related sustainability, with the mainly mentioned categories referring to environmental impact, locally and organically sourced food, and ethical production. However, modern literature reveals that consumers still lack crucial knowledge on certain specific topics related to food sustainability. Notably, they struggle to define "sustainability" and to assess the environmental impact of their food choices. Overall, consumers believe that sustainability is not the main criterion for their food purchasing decisions. Presently, factors such as price, taste, and individual health are considered more influential than sustainability [22,23].

Consumers' opinions on plant protection products reflect their growing understanding of the environmental and health risks of agricultural operations. Their behavior has been altered due to the abundance of information and purchase of food that satisfies demanding standards, especially concerning the use of environmentally friendly pesticides. As we navigate the difficulties that contemporary agriculture must confront, we must make progress in developing creative solutions that promote environmental sustainability, public health, and socioeconomic well-being. We must reduce our dependency on chemical pesticides and increase the utilization of alternatives to secure the health of the agricultural environment and thus allow sustainable agriculture to be an achievable objective [24,25].

2.2. Producer Perceptions

Producers have depended on pesticides for a long time to protect their crops against many threats, including diseases, arthropod pests, weeds, and nematodes. Their objectives involved enhancing food production quality and guaranteeing that yields could be sustained over an extended period [26]. Unfortunately, the improper use of pesticides has resulted in a rise in the development of pesticide resistance, which has, in turn, severely influenced ecosystems and people's health [27].

The social side of the problem is closely related to the demographic makeup of the agricultural industry and the farmers employed within it. Compared to developing countries, industrialized nations have a far higher success rate in adopting new technology to carry out ordinary duties. It is of the utmost importance to have a fundamental comprehension of the process by which technology functions and the capabilities it has [28–32]. As producers tend to be older on average, they have much higher levels of education and living conditions. Consequently, this leads to a complete grasp of technical ideas and functions, including protecting health, preserving the environment, and maintaining economic efficiency.

Regarding farming, offering a standard framework for using joint integrative pest management (IPM) techniques is challenging because each crop has its unique set of criteria that must be met. Precision spraying and other precision agricultural approaches are advocated to reduce harmful effects [33,34]. Refs. [35,36] revealed that producers are

interested in using novel technologies, concluding that the demographics were not the key drivers of IPM adoption. The socioeconomic environment of the nation, the kind of agriculture and agricultural production, and the country's geographical location and climate may be possible drivers of IPM [33,37].

Furthermore, small-scale producers with few resources are less likely to accept these practices due to their lack of knowledge, awareness, and financial assistance [8,9]. On the contrary, those who operate on a larger scale often need more resources to accomplish the move. The frequency and kind of weeds and insects that farmers must deal with, as well as the efficacy of the treatments used, are all influenced by various geographical factors [38,39].

3. Materials and Methods

3.1. Survey Instrument

The structured questionnaires addressed to producers and consumers were designed to identify the main determinants of production and consumption for new innovative plant protection products that could be developed and made available as low-risk agrochemicals. The objective was to collect primary data and construct a composite index reflecting how climate change and environmental constraints influence the attitudes of consumers and producers towards methods combating harmful organisms used in crop production. Additionally, this research investigates how these factors, along with capital, land, and human resources constraints, impact producers' decisions to adopt these tools, including economic dimensions such as net added value and employment.

The drafting of the questionnaire began in July 2020 and was completed in August 2020. The questions in each questionnaire were derived from an extensive review of relevant international literature, with necessary modifications to align with the research focus and the crops under examination [29,30,39–47]. Apart from questions already validated and reliable from the literature review, the questionnaire also included questions that were developed in the pilot study. The five sections of the questionnaire for olive, tomato, and citrus crop producers included, first, questions related to the personal information of producers to create their demographic profiles. The second section had eleven questions regarding farming practices and various economic aspects. The third section contained seven questions about producers' attitudes towards environmentally friendly pest control methods/tools and their sources of information on these tools. The fourth section consisted of ten questions about producers' attitudes toward pesticide application, including the type and origin of pesticides used. The fifth section of the questionnaire included five questions about producers' attitudes towards the environment and climate change.

Following a similar process, the consumer questionnaire was developed in July–August 2020. Questions were based on a comprehensive review of relevant international literature, with necessary adaptations to match the research objectives and the examined crops [47–52]. Accordingly, most of the questions included in the survey instrument for consumers were validated and reliable stemming from the literature review. This questionnaire comprised two main sections. The first section included 28 closed-ended questions concerning consumers' attitudes and perceptions towards innovative environmentally friendly pest control tools (EFCTs). Specifically, questions were formulated regarding consumers' purchasing behavior towards products produced using such tools, their attitudes towards food, and questions related to the environment and climate change control. The second section of the questionnaire contained questions about consumers' demographic information and education level.

Sampling was conducted in two stages. In October 2020, the first stage involved conducting a pilot study with a sample of 20 producers to collect data for the preliminary questionnaire validation. Initially, the questionnaire was examined for its syntactic, semantic, and objective adequacy. Although there were no substantial problems with the questionnaire's structure, a second check during the pilot study was conducted to estimate the average time required to complete it, along with some observations and suggestions for

conceptual adequacy and structural improvement. The validation was performed through personal interviews with olive, tomato, and citrus crop producers. The questionnaires for producers and consumers took their final form (some questions were reformulated, and others were removed due to their non-significant contribution to the research). The next stage involved the actual collection of questionnaires.

The sample for this research consists of 583 questionnaires, specifically comprising 477 consumer responses and 74 producer responses. As for the consumer sampling procedure, we implemented random sampling to develop the final sample for consumers. The population size was the total Greek population (10,782.487 citizens), and with a confidence error of 98% and margin error of 5%, the minimum number of necessary samples to meet the desired statistical constraints was 543 respondents. Hence, after validating the sample, the questionnaire was uploaded to social media through Google Forms to obtain the responses.

As for the producer sampling procedure, we aimed mainly at producer associations who cultivate olives, citrus, and tomatoes. Since sending the questionnaire electronically entailed certain risks, the decision was to personally interview the specific producers. Accordingly, producers who were based in Northern Greece (Central Macedonia and Anatoliki Makedonia and Thraki) were chosen to synthesize the final sample, mainly to minimize the cost of the survey. Each producer was initially contacted via telephone to confirm his/her participation in the study, and a meeting was scheduled to answer the questionnaire. Given the specific constraints that exist when surveying producers (i.e., unavailability, reluctance to expose economic data, cultivation period, etc.), 74 producers from the three cultivation types finally answered the questionnaire.

3.2. Methods

The collection of questionnaires was followed by a statistical analysis aiming initially at analyzing the demographic profile of the three respondent categories. Subsequently, the goal was to identify the factors that explain their attitude toward using environmentally friendly pesticides and, more generally, actions related to environmental protection. One additional statistical analysis was performed before estimating logit models and categorical regressions, namely factor analysis. Factor analysis aimed to identify factors in the case of multi-thematic questions, a process followed in both respondent categories. The data reduction technique used was Principal Component Analysis (PCA) with a Varimax rotation and an eigenvalue greater than one as the extraction criterion. Subsequently, a regression model used the factors extracted as variables (Figure 2).

Logistic Regression Model

A multivariate statistical analysis approach known as logistic regression is used to study the behavior of a categorical dependent variable that is dichotomous and categorical [53,54]. This method uses a collection of independent factors to interpret the behavior of the dependent variable. Using this strategy, we can predict the existence or absence of a particular element or event. Because the objective is to evaluate the likelihood of a specific event's occurrence, the values derived from the linear model lie within the interval [0, 1]. For this reason, we assume that the variable follows a binomial distribution and the connection of the probability of the event occurrence p_i is linked to the linear model through the logit function:

$$logit(p) = \ln(odds) = \ln(p/(1-p)) = b_0 + b_1X_1 + b_2X_2 + \ldots + b_kX_k \quad (1)$$

where

- p is the probability of the dependent variable;
  $odds = \frac{p}{1-p}$ are the odds of the dependent variables;
- $X_1, X_2, \ldots, X_k$ are the independent variable or maximum likelihood estimators;

- $b_0, b_1, b_2, \ldots, b_k$ are the model's coefficients that must be determined to maximize the likelihood of the observed sample values.

  Equation (1) can be written as follows:

$$odds = \frac{p}{1-p} = e^{b_0} * e^{b_1 X_1} * e^{b_2 X_2} * \cdots * e^{b_k X_k} \quad (2)$$

Therefore, the interpretation of each coefficient in the above equation is that when the variable X_k changes by one unit, with all other factors remaining constant, the odds will change by a factor of e^{b_k} . A coefficient with a positive (negative) sign indicates that an increase in the corresponding independent variable will increase (decrease) the relative probability of the dependent variable.

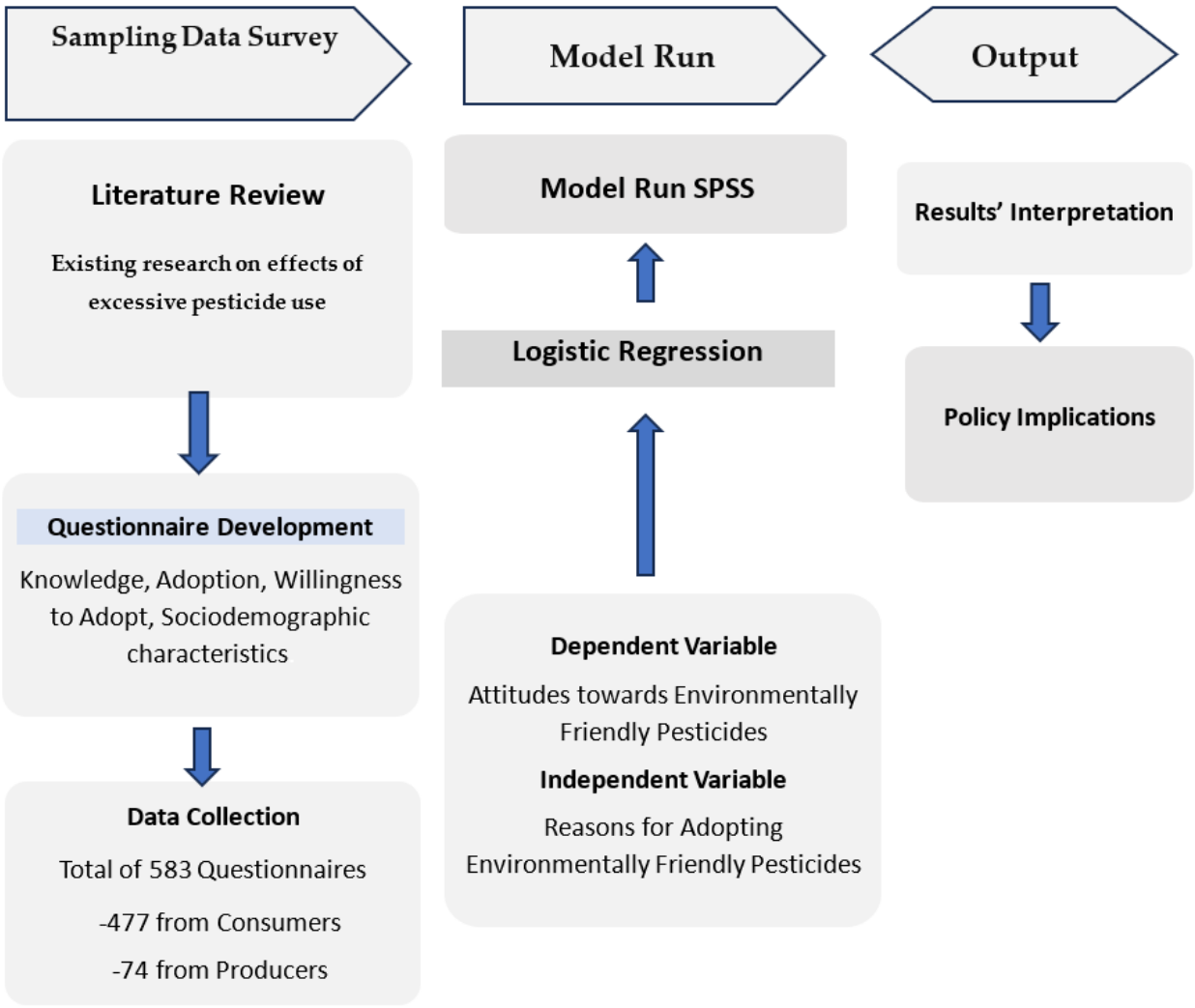


Figure 2. Flow chart of the methodology.

Finally, the probability of the event is calculated using the inverse logit function in the following Equation (3):

$$p = \frac{1}{1 + e^{-logit(p)}} \quad (3)$$

In logistic regression models, the coefficients are estimated via the maximum likelihood method instead of the least squares method. The coefficients of the model undergo significance testing. The hypothesis under consideration is

$$H_o : \hat{\beta}_i = 0$$

$$H_1 : \hat{\beta}_i \neq 0$$

The test is conducted at a significance level of α %, and the statistical function under H_0 is the Wald function, which asymptotically follows the normal distribution. The square of this function follows the X^2 distribution with 1 degree of freedom. The hypothesis is rejected if the test value exceeds $X^2_{1;\alpha/2}$ [54].

Model comparison for selecting the optimal model is carried out using the Deviance statistic, essentially a likelihood ratio test, defined as $D = -2\left\{\hat{l}_2 - \hat{l}_1\right\}$.

Where

- $\hat{l}_2$ is the deviance of model 2;
- $\hat{l}_1$ is the deviance of model 1. Additionally, model 2 is a subset of model 1 and follows the X^2 distribution with k-p-1 degrees of freedom [54].

4. Results

This section, firstly, presents the results of a statistical analysis focusing on the demographic characteristics of 474 consumers surveyed. Regarding their gender, the majority were females (50.7%), and a significant portion of the sample was aged within the interval 18–25. Regarding marital status, a high percentage were married (41%), with most having four children. A small percentage of households involved individuals over the age of 65. Concerning the income class, most respondents fell into the second, third, and fourth classes, with incomes ranging from 500 to 2000 euros per month. Approximately 50% of respondents had full-time employment, while 22% of the respondents' spouses were unemployed. It is worth noting that most respondents were public employees, and their level of education was significantly high.

As for the surveyed producers, based on the demographic analysis, we observed that most respondents were men aged 21 to 39 years old, married, and highly educated. Their income ranged from 10,000 to 20,000 euros per month, with the production cost being less than 50% of their income. In contrast, most do not belong to a cooperative (61.8%) or other producer association (78.9%). In contrast, the percentages of respondents belonging to a cooperative (38.2%) or a union (21.1%) were very low. The demographic profiles of consumers and producers are provided in Appendix A in Tables A1 and A2, respectively.

4.1. Results of Factor Analysis

Consumers

Multifaceted questions from the consumer questionnaire were selected to contribute to constructing indicators. Before conducting these procedures, the reliability was checked using the Kaiser–Meyer–Olkin Measure of Sampling Adequacy criterion, with estimated values ranging from 0.69 to 0.8 in all cases, i.e., close to 0.7, indicating the sampling adequacy. Based on the analysis findings, the question addressing food consumption criteria includes three factors: criteria related to their contribution to health, their contribution to weight control, and the taste and aroma of the food (Table 1). The factors that were extracted representing the mentioned criteria were FC1 (Purchase of products based on health), FC2 (Taste and aroma criteria), FC3 (Purchase based on weight control), FC4 (Label and product promotion criteria), FC5 (Price and taste criteria), FS1 (Consumer perceptions of adopting practices by producers regarding food safety), EP1 (Environmentally friendly actions), EP2 (Modes of transportation) and EP3 (Indifference/ignorance about environmentally friendly actions). Consumers' perceptions of adopting practices from producers regarding food safety were also investigated. Only one factor (FS1) was extracted, which explains 82.4% of the variance explained by this multifaceted question. Finally, the pro-environmental policies adopted by consumers in their daily lives were also explored, and three factors were confirmed: EP1 (Environmentally friendly actions), EP2 (Modes of transportation), and EP3 (Indifference/ignorance about environmental practices).

4.2. Producers

Specific questions with a wide range of features were selected from the questionnaire sent to the producers to facilitate the development of appropriate indicators. We used the Kaiser–Meyer–Olkin Measure of Sampling Adequacy to determine whether the samples were reliable. In every case, the estimated value was between 0.698 and 0.8, which is close to 0.7, suggesting that the sampling was sufficient. After careful consideration, the criteria were divided into economic, environmental, and customer-centric. This was carried out via factor analysis to ascertain the reasons for implementing activities that benefit the environment. According to Table 2, the factors that were extracted were B1 (Economic criteria), B2 (Environmental criteria), B3 (Customer-centric criteria), B4 (Effectiveness of environmentally friendly products), B5 (Perceptions of pesticide impacts), and B6 (Necessity and favorable effects on performance and production). Producers' reasons for adopting environmentally friendly practices were also investigated. Only one factor (B4) explains 77% of the variance extracted. Finally, the barriers to implementing environmentally friendly plant protection methods/tools were also explored, and several factors were confirmed, highlighting the complexity of these decisions.

Table 2. Factor analysis of the consumers' food consumption criteria.

Code	Criteria	Loadings	Variance Explained
FC1	Purchase of Products Based on Health		80%
	Contains many vitamins	0.845	
	Helps me stay healthy	0.823	
	Is nutritious	0.825	
	Does not contain additives or preservatives	0.668	
	Contains natural ingredients	0.746	
	Does not contain artificial ingredients	0.772	
FC2	Taste and Aroma Criteria		80%
	Smells nice	0.855	
	Looks nice	0.874	
	Has a nice taste	0.732	
FC3	Purchase Based on Weight Control		80%
	Has low calories	0.891	
	Helps me control my weight	0.819	
	Has low fat	0.801	
FC4	Label and Product Promotion Criteria		80%
	Producer/label	0.824	
	Recommendation from known/friend	0.812	
	Adoption of environmentally friendly practices indication	0.590	
	Producer/label	0.824	
FC5	Price and Taste Criteria		80%
	Price	0.693	
	Taste		
FS1	Consumer Perceptions of Adopting Practices by Producers Regarding Food Safety		82,4%
	Sufficient ability to control food safety	0.856	
	Necessary knowledge to ensure food safety	0.870	
	Honest about food safety	0.942	
	Inform about food safety	0.906	

Table 2. *Cont.*

Code	Criteria	Loadings	Variance Explained
FS1	Pay attention to food safety	0.944	
	Particularly interested in food safety	0.925	
	Sufficient ability to control food safety	0.856	
	Necessary knowledge to ensure food safety	0.870	
EP1	Environmentally Friendly Actions		67%
	Separation of most waste for recycling	0.634	
	Reduction of energy consumption	0.782	
	Reduction of water consumption	0.890	
	Reduction of consumption of disposable items	0.810	
	Choosing local products or grocery items	0.742	
	Purchase of environmentally friendly products with relevant labeling	0.752	
EP2	Modes of Transportation		67%
	Choosing environmentally friendly modes of transportation (walking, cycling, public transportation)	0.668	
	Restriction on car usage	0.831	
EP3	Indifference/Ignorance About Environmentally Friendly Actions		67%
	None of these	0.837	
	Others	0.695	
	Don't know	0.669	

Own calculations.

Factor analysis was performed to explore the actions that limit climate change and potentially affect the farm's performance. Seven factors were extracted (Table 3): B1 (Criterion of health and environmental impacts), B2 (Economic and practical efficiency), B3 (Sources of influence on the pesticide market), B4 (Perception of environmental impacts of agriculture), B5 (Adoption of strategies to mitigate climate change), B6 (Impacts of climate change limitation), and B7 (Measures limiting climate change impact on business). Producers' barriers to implementing environmentally friendly production methods were also investigated, and only one factor (B6) explains 90% of the variance extracted.

Table 3. Factor analysis for the producers' reasons for adopting environmentally friendly practices.

Code	Reasons For Adopting Environmental Practices	Loadings	Variance Explained
B1	Economic Criteria		81%
	Higher profitability	0.737	
	Increased production	0.817	
	Availability of environmentally friendly tools	0.658	
	Farm size	0.829	
	Experience in pesticide use	0.666	
	Local pressures of pests or diseases for pesticide application	0.690	
	Low overall cost compared to conventional methods	0.820	
	Resistance/efficacy of pesticides	0.619	

Table 3. *Cont.*

Code	Reasons For Adopting Environmental Practices	Loadings	Variance Explained
B2	Environmental Criteria		62%
	Better agricultural product	0.592	
	Conventional pesticides are not sustainable	0.537	
	Reduction of the impact of pesticides on the broader area	0.750	
	General scientific warning of environmental risk from the use of conventional pesticides	0.658	
	Less use of fertilizers	0.900	
	Development of reduced-risk pesticide strategies	0.911	
B3	Customer-Centric Criteria		74%
	Increased product demand	0.837	
	Imposed food safety standards	0.615	
	Premium paid-for environmentally friendly products	0.761	
	The high price of the final product	0.879	
	Increased consumer awareness	0.778	
	Barriers to the implementation of environmentally friendly plant protection methods/tools		77%
	Contribution of technical knowledge		
	Lack of knowledge about innovative plant protection tools	0.800	
	Lack of training	0.837	
	Insufficiency of innovative plant protection tools	0.851	
	Availability of pesticides	0.665	
	Lack of coordination between producers and agricultural consultants	0.777	
	Fear of the effectiveness of innovative plant protection tools	0.753	
	More time is needed to achieve the expected result	0.567	
	No distinction regarding the price of environmentally and non-environmentally friendly products	0.834	
B4	Effectiveness of Environmentally Friendly Products		77%
	More time is needed to achieve the expected result	0.735	
	Requires more labor	0.823	
	Effectiveness of biological control factors	0.666	
B5	Perceptions of Pesticide Impacts		78%
	Adverse effects of pesticides on humans	0.806	
	The harmful effects of pesticides may be severe	0.885	
	Pesticides affect human health	0.895	
	Pesticides enter the body through the skin	0.824	
	Pesticides enter the body through the mouth	0.868	
	Pesticides enter the body through the nose	0.885	
	Pesticides affect animals	0.892	
	Pesticides affect the environment	0.834	

Table 3. *Cont.*

Code	Reasons For Adopting Environmental Practices	Loadings	Variance Explained
B6	Necessity and Favorable Effects on Performance and Production		74%
	There could be alternative solutions for pesticides in my production	0.854	
	Pesticides are necessary for high yield and product quality	0.815	
	Pesticides are necessary in my production	0.805	
	The body can develop immunity to pesticides	0.831	
	Higher toxicity or a mixture of pesticides can improve crop production	0.895	
	Pesticides affect soil fertility	0.613	

Own calculations.

4.3. Model Estimation Results for Consumers and Producers

Consumers

For this regression analysis, the dependent variable was the chance of selecting things certified for their protection utilizing environmentally friendly plant protection equipment instead of those subjected to a conventional manufacturing process. To provide more clarification, the fixed-term model seems to merely interpret, in a manner that is not statistically significant, the willingness of consumers to pay a higher amount than the price that is now being offered. A second categorical regression was analyzed within the scope of the data analysis to discover the factors that affect the consumers' willingness to pay a higher price than the existing price for food protected by environmentally friendly plant protection products.

According to the results of the estimated model, it was concluded that each of the determinants had statistical significance. The consumers' willingness to pay more for food is subject to eco-friendly plant protection increases with age (a higher priority is given to good nutrition), working time (also a priority for people with long working hours is good and quality nutrition), their positive attitude towards foods that have eco-friendly plant protection, the taste, and labeling of products for eco-friendly plant protection use, as well as their perception of producers' attitudes and knowledge of food safety issues (Table 4). In addition, concerning the lower probability (unwillingness) to pay more than the current price, the country of origin has a more significant impact on leisure time, education (the lower the level of education, the lower the willingness to pay more), indifference, and lack of information of consumers about food products to which eco-friendly plant protection are applied. Explicitly, all the above factors function as barriers to the consumers' willingness to pay more.

Table 4. Factor analysis for the producers' barriers to implementing environmentally friendly production methods.

Code	Factors	Loadings	Variance Explained
B1	Criterion of Health and Environmental Impacts		77%
	Ingredients—judged by their impact on health	0.933	
	Ingredients—judged by their impact on the environment	0.902	
	Package warnings regarding impacts (labeling)	0.846	
B2	Economic and Practical Efficiency		
	Ingredients—judged by their effectiveness against pests	0.885	

Table 4. *Cont.*

Code	Factors	Loadings	Variance Explained
B2	Personal experience with the product from previous use	0.745	
	Price	0.881	
B3	Sources of Influence on the Pesticide Market		
	Producer	0.658	
	Recommendations from friends	0.831	
	Recommendations from sellers	0.717	
	Other factors	0.497	
	Interpretative ability of variability		78%
B4	Perception of Environmental Impacts of Agriculture		
	Negative impacts due to fertilizers		
	Environmental burden due to excessive use of chemical fertilizers	0.743	
	Environmental burden due to excessive use of pesticides	0.836	
	Pollutes the water horizon more than other cultivations	0.728	
	Burdens the environment as well as other cultivations	0.729	
	Positive impacts		
	Burdens the environment due to increased water needs	0.463	
	Linked to positive impacts on the environment/landscape	0.921	
	Aids in the conservation of the environment and natural resources	0.894	
	Interpretative ability of variability		69%
B5	Adoption of Strategies to Mitigate Climate Change		
	Environmentally friendly cultivation practices	0.911	
	Less polluting fertilizers and pesticides	0.907	
	Use of renewable energy sources	0.831	
	Energy-efficient practices	0.851	
	Irrigation and none		
	Irrigation practices	0.760	
	None	0.804	
	Interpretative ability of variability		78%
B6	Impacts of Climate Change Limitations		
	Will worsen my and my family's health	0.959	
	Will reduce the profitability of my operation	0.995	
	Will degrade the quality of my products	0.991	
	Will worsen the living standards in society	0.948	
	Interpretative ability of variability		9%

Table 4. *Cont.*

Code	Factors	Loadings	Variance Explained
B7	Measures Limiting Climate Change Impact on Business		
	Environmentally friendly cultivation practices	0.867	
	Less polluting fertilizers and pesticides	0.862	
	Use of renewable energy sources	0.890	
	Energy-efficient practices	0.876	
	Irrigation practices	0.890	
	None	0.315	
	Interpretative ability of variability		9%

Finally, consumers' perceptions of producers' intention to certify their products and adopt such practices enhance the probability of paying more in a statistically significant way. Even though the rates were far lower, the impacts were equivalent to the increased prices of other products, which were significantly more substantial.

4.4. Producers

In dichotomous regression, we used the producer's willingness to replace conventional plant protection products with environmentally friendly products as the dependent variable. Several demographic characteristics were used as independent variables, incorporating reasons for adopting or preventing the use of ECR, climate change's economic and environmental impacts, and variables linked to obstacles or producers' attitudes and actions towards the environment. The results of the model estimation are provided in the following Tables 5 and 6.

Table 5. Estimation results of consumer willingness to pay for products with pesticide residue.

		B	SIG.	EXP(B)
	Constant Term	2798.805 ***	0.000	
	Percentage of fruits and vegetables consumes per week	−26.683 ***	0.000	2.580×10^{-12}
	Contribution of country of origin	−4014.449 ***	0.000	0.000
	Education	−387.578 ***	0.000	4.752×10^{-169}
	Free time	−252.725 ***	0.000	1.750×10^{-110}
	Age	423.010 ***	0.000	5.142×10^{183}
	Working hours	221.387 ***	0.000	1.403×10^{96}
B1	Adoption of environmental actions	280.143 ***	0.000	4.619×10^{121}
EP1	Preferences for purchasing items using environmentally friendly plant protection products	302.079 ***	0.000	1.554×10^{131}
FC4	Indifference and ignorance products with pesticide residue	−1762.301 ***	0.000	0.000
FC4	Label	−101.905 ***	0.000	5.534×10^{-45}
FC5	Taste	655.204 ***	0.000	3.559×10^{284}
FC4	Labeling for adopting environmental practices	251.268 ***	0.000	1.331×10^{109}
B6	Perception of producers' knowledge of food safety and certification	112.200	0.023	8.504×10^{139}

*** Rejection of null hypothesis at the 5% level of significance.

Table 6. Estimation results of a dichotomous regression model for producers.

	Variables	Coefficient
	Reasons for environmental protection	14.2 ** (0.03)
B2	Economic reasons	2.692 *** (0.00)
	Others	0.221
	Government policy	0.933 ** (0.03)
	Lack of education and information	4.325 *** (0.01)
	Effectiveness and adequacy of ECR	2.192 * (0.08)
	Perception of a significant impact of ECR on income	2.4 ** (0.04)
	Perception of the social impact of climate change	3.24 ** (0.04)
	Understanding the environmental impact of climate change	2.692 * (0.08)
	Understanding the economic impact of climate change	31.62 *** (0.000)
	Age	−10.8 *** (0.01)
	Education (master's)	5.833 *** (0.01)
	Education (PhD)	4.2 ** (0.04)
	Production cost	−2.11 ** (0.03)
	Perception of a significant change due to climate change in agricultural income	4.2 ** (0.04)

* Statistically significant at $p < 0.1$; ** Statistically significant at $p < 0.05$; *** Statistically significant at $p < 0.01$.

Farmers are affected by demographic characteristics such as education level or age when deciding whether to use environmentally friendly plant protection solutions. Those with master's or PhD degrees are more receptive to implementing ecologically friendly practices due to their knowledge. Furthermore, the perceptions of the income repercussions of climate change might have a statistically significant impact on this result. Environmental and economic factors have a positive and statistically significant effect on the willingness of farmers to replace conventional pesticides with environmentally friendly plant protection. Thus, environmental and economic factors are critical to the probability of adopting environmentally friendly plant protection.

On the other hand, the choice to use ecologically friendly plant protection rather than conventional protection is limited by the higher costs attached to the decision. Furthermore, the decision to prefer ecologically friendly plant protection over conventional pesticides is determined by the individual's comprehension of the social and environmental ramifications of climate change and their expectation to experience the effects of climate change. Additionally, in line with those mentioned above, adopting laws that will ensure decreased pricing and enhance the knowledge and awareness of farmers may enable the replacement of conventional pesticides with environmentally friendly plant protection. This is because the laws will guarantee that farmers understand the situation. However, we should mention that the data deficiency was a significant barrier to gathering conclusions on the degree of adoption in terms of individual crops.

5. Discussion

5.1. Consumers

In most of the consumer demographics that were questioned, the respondents were females who were employed in the public sector, between the ages of 18 and 25, and had a high education level. Notably, even when presented with a higher price point, these consumers showed a common inclination to choose environmentally friendly food (EFF) rather than conventional goods. This is an important finding highlighting the preference for EFF due to female sensitivity and environmental benefits. Surprisingly, despite the consumers' high need for EFF, they are reluctant to switch grocery stores for their pre-

ferred type of food. This underscores the importance of the sources of products and the marketplaces in the local area. There was a distinct trend of consumers who avoided synthetic and organic pesticides, and this pattern was detected by the respondents of the survey. The participants have phrased their concerns over the potential adverse effects on their health brought about by chemical pesticides, while the consumers' knowledge of the environmental impact caused by pesticides stresses the product certification significance as a criterion to be preferred.

It was revealed that the key driving factors for consumers' desire for this product were the flavor of EFF as well as the health benefits that have been associated with it. Furthermore, the role of EFF in the control of weight was taken into consideration. In contrast, the survey results revealed an extensive knowledge gap among consumers about food safety and that producers have a lack of openness regarding information. Regarding food safety, most consumers believed that manufacturers did not pay sufficient attention to or place adequate significance on the matter.

A commitment to recycling, a reduction in the use of disposable items, a preference for locally produced goods or brands sold at grocery stores, the purchase of products that are branded with an environmental label, and a deliberate attempt to reduce the amount of time spent driving their cars are all examples of environmentally friendly behaviors that customers have demonstrated.

Moreover, the logit model estimation results have validated the statistically significant impact of product certification on the consumers' willingness to spend extra money on those products. In addition, a rise in this willingness is related to age. This contradicts the findings of the first investigation, which suggested that there was a low statistical significance in the consumers' willingness to pay more for EFF in comparison to conventionally produced agro-food products. A number of variables were validated as statistically significant, including a greater emphasis on a good diet, perspectives that were positive towards EFF, as well as worries surrounding working hours, the effect of product labeling, and opinions regarding the knowledge and intentions of producers regarding safety. These results provide an insight into the preferences and behaviors of the consumers who were surveyed concerning environmentally friendly food choices.

The current study highlights the growing awareness among consumers about environmental and health concerns, which in turn impacts their choices for alternatives that are both environmentally friendly and devoid of substances that include pesticides. The findings of Dyck et al. [12] indicate that consumers are becoming more aware of the environmental and health risks involved with agricultural production and are also getting more worried about these risks. This is consistent with the more significant trend of consumers opting for environmentally friendly and sustainable products in their production and consumption systems. Specifically, the positive aspects of age and the importance consumers place on nutrition are significant factors influencing consumer behavior regarding willingness to pay a premium for environmentally friendly plant protection methods, as indicated by dichotomous regression analysis. Favorable attitudes and perceptions toward environmentally friendly products, flavors, and environmental labeling increase the likelihood of consumers paying a premium for such items. In addition, consumers who have favorable perceptions are more likely to pay a premium for these products.

On the other hand, a significant number of attributes have a detrimental impact on a consumer's readiness to pay. The nation of origin and education are the first of these factors. Lower levels of education are linked to a decreased willingness to spend, highlighting the crucial role of education in shaping consumer attitudes. Conversely, higher levels of education are associated with a greater desire to spend. Free time and indifference are also significant variables, as consumers with limited leisure time are indifferent to products that include pesticide residue, and consumers who lack information about products that contain pesticide residue are less likely to pay for them. This is probably a metaphor for busy consumers' challenges and the value of information in influencing their choices throughout their hectic lives.

The study underlines the relevance of education in terms of its power to affect the knowledge and behavior of customers, which reaffirms the results that [45] discovered. Since there is a link between more significant levels of knowledge and an increase in the desire to spend, consumers must make choices based on correct information. Furthermore, various criteria, such as economic parameters, circumstances specific to a country, and educational levels, all play a role in determining whether consumers are willing to support environmentally friendly habits. These results align with those of [35], who indicated that the socioeconomic context is one of the most significant aspects that play a role in determining the behavior of consumers.

The results of the consumer willingness-to-pay regression offer valuable insights into the complicated interaction of factors that impact purchasing decisions associated with food that is produced utilizing environmentally friendly plant protection. Age, positive attitudes, environmental awareness, and trust in producers seem to be good drivers. At the same time, economic worries, education levels, and traits peculiar to the nation appear to be obstacles. All the factors mentioned above present a comprehensive understanding of consumer behavior and show the necessity of concentrated awareness efforts, education initiatives, and regulatory measures to promote environmentally responsible agricultural methods and meet the ever-changing expectations of consumers. In terms of education, workshops and seminars on topics like sustainable farming practices, organic products, and the impact of agriculture on the environment, as well as the incorporation of agricultural education into school curriculums and the distribution of brochures, flyers, and booklets with information on different agricultural products and their benefits could be some examples. Further strategies to be adopted are related to labeling and certification, campaigns promoted on social media, as well as collaboration with influencers. Policy interventions could include initiatives that support agricultural education and the promotion of sustainable farming practices as well as public service announcements to inform consumers about the benefits of sustainable agriculture and responsible consumption, and collaboration with non-governmental organizations that focus on sustainability and agriculture to amplify the reach and impact of awareness campaigns. A final but certainly significant step that could be taken involves providing consumers with information on the origins and production methods of their food and implicitly promoting transparency in the supply chain. The combination of the above strategies could change the prioritization of the agro-food selection criteria for consumers, promoting sustainable agriculture.

5.2. Producers

Several factors significantly impacted the limited adoption of environmentally friendly technology, including efficacy, sufficiency, and knowledge levels. Farmers raised concerns about pesticide use, highlighting issues such as the availability of alternative pesticides, the impact on animals and the environment, and soil fertility.

Due to the selection criteria of effectiveness, price, prior experience, and health concerns, botanical pesticides emerged as producers' preferred alternative. The advent of other options that are less harmful to the environment coincided with a considerable movement toward using conventional pesticides. Price stability was highlighted as a primary factor in this transformation. Even though many farmers used environmentally friendly irrigation and growing processes and environmentally friendly agricultural products, there was less interest in adopting techniques connected to renewable energy sources and energy efficiency. This was the case, although there was much interest in adopting these techniques.

From the producers' point of view, it was challenging to ascertain the effect that implementing environmentally friendly practices would have on the money generated by agricultural production. Several vital characteristics contributed to the producers' desire to replace traditional commodities with environmentally friendly alternatives. These included education and age and the farmers' expectations of climate change's impact on agricultural earnings. The desire of farmers to replace conventional pesticides with alternatives that

are less harmful to the environment was positively influenced by environmental and economic factors; nevertheless, the high pricing of these alternatives proved a limiting factor throughout this process. Producers' awareness and concern about climate change's social and environmental repercussions influenced their decision to include environmentally friendly products in their production process.

Based on the research findings, it was suggested that it might be possible to replace conventional pesticides with less harmful alternatives to the environment if specific regulations were implemented to ensure that prices were reduced and if educational activities were implemented to promote awareness among growers. The main issue within the Green Deal involves a fast-track approval [55] for the low-risk products that are on the 2018 list, without waiting for the renewal of these substances, and the extension of their current use to crops (more in horticulture) and in IPM regimes [56]. In terms of stakeholders, the following are needed: financial incentives, providing training and information, recruitment of specialists, a faster approval track, and the sponsoring of research projects.

Several categories are brought to the forefront in analyzing the factors that influence the choice of pesticides. Producers pay attention to components that positively affect the health of the people and the environment. The significance of labeling and warnings on products throughout the decision-making process highlights the critical role of information that is open and accessible. Furthermore, economic factors, such as the effectiveness of pesticides, personal experience, and price, have a substantial influence. The prioritization of compounds that are reviewed based on their effect on health and the environment and the relevance of warnings and labels on packaging is matched with the improved awareness of the harmful repercussions of indiscriminate pesticide use. The emphasis on this subject aligns with other studies [27,40] that emphasize the shift toward environmentally conscious decision making.

Farmers are concerned about the potential negative impacts that an excessive number of chemical fertilizers and pesticides may have on the environment. As may be seen from the emphasis that is being put on environmental burden and water pollution, there is a heightened understanding of the more considerable ecological consequences that agricultural activities have. In addition, recognizing the positive outcomes, such as contributing to the preservation of natural resources and the protection of the environment, indicates a sophisticated understanding of agriculture's dual role in contributing to and relieving environmental problems. Previous studies have also reached the same conclusions [31,45,57].

In alignment with adopting climate change mitigation strategies, producers are committed to implementing environmentally friendly cultivation practices and using less polluting fertilizers and pesticides. More specifically, within the Green Deal Agreement, the adoption of low-risk pesticides of biological origin as an alternative to chemical pesticides in agriculture is a requirement in order to realize the Farm to Fork strategy target of a 50% decrease in the use of more hazardous pesticides by 2030 [58]. This objective can be achievable with measures taken by each member state, including financial incentives, training and information provisions, the recruitment of specialists, a faster approval track, and the sponsoring of research projects. Additionally, the role of demographics, socioeconomic conditions, and geographic factors in shaping acceptance levels of innovative practices is consistent across various studies.

The regression model delves into the determinants impacting producers' choices regarding adopting eco-friendly plant protection products over conventional pesticides. The results show a positive correlation between higher education levels and a greater inclination to adopt eco-friendly plant protection, highlighting the crucial role of education in environmentally conscious decisions. Additionally, a negative coefficient for age suggests younger producers are more likely to replace conventional pesticides, indicating a generational shift in preferences.

The viewpoints that farmers have on the impact that climate change might have on the profitability of agriculture represent an additional significant element that should be considered. It may be deduced that producers who are aware of the consequences of

climate change are more likely to use techniques of plant preservation that are less harmful to the environment. This highlights how essential it is to be conscious of climate change to establish agricultural practices responsible for the environment. Producers driven by economic viability and environmental sustainability will likely adopt eco-friendly plant protection methods. This reflects an international trend toward balancing economic and ecological considerations.

Even though environmental and economic incentives positively impact adoption, the model suggests that the higher costs connected with the maintenance of ecologically friendly plants are a factor that limits adoption. Consequently, this reflects producers' economic challenges while transitioning towards more sustainable practices, highlighting the need to find more cost-effective alternatives. There is a significant relationship between producers' knowledge and interest in the social and environmental implications of climate change and their decision making. Considering this, environmental consciousness and social responsibility play a significant role in the decision-making process within the agricultural sector. Producers' perception of their competence in food safety and certification is one of the variables that has a favorable influence on the customers' willingness to pay for the product. When it comes to altering the behavior of consumers, confidence in producers and their dedication to adopting environmentally friendly solutions are extremely significant considerations.

According to the concept, policy measures that aim to lower the number of barriers that inhibit adoption are the ones that should be pushed for. Possible steps to facilitate the transition to environmentally friendly plant care would be to decrease expenses while simultaneously boosting the level of knowledge and awareness among farmers. When it comes to developing and implementing such measures, policy makers are strongly urged to consider the socioeconomic context, which encompasses a variety of characteristics like education level, age, and economic circumstances. The results emphasize the crucial role of farmer education in understanding pesticide consumption consequences and promoting sustainable practices, coinciding with the arguments of [45].

In line with [35], it is widely acknowledged that the socioeconomic characteristics of a region play a significant role in determining the degree to which eco-friendly behaviors are accepted. The effect of geographical location and climatic conditions on farmers' willingness to apply integrated pest management (IPM) techniques aligns with previous research findings [38,39], particularly in the same region, as indicated by the present study. Small-scale producers are more reluctant than larger producers, often due to a lack of technical expertise and financial resources.

The study's results highlight the necessity of implementing interventions tailored to the specific environment in which they are being applied. Additionally, it is essential to emphasize that the model acknowledges the complexities and challenges inherent in migrating to new plant protection measures, consistent with the studies of [59,60].

Considering all the criteria mentioned above, the findings offer valuable insights into the plethora of antecedents that affect producers' adoption of environmentally friendly plant protection products. Obviously, the issues of education, knowledge, economic concerns, and measures taken by the government are all significant factors. Policy makers are encouraged to devise solutions to these issues to establish a sustainable and environmentally friendly agricultural sector. The model's alignment with past research highlights the need for coordinated efforts to promote eco-friendly agricultural practices and tackle global pesticide-related problems, contributing to the robustness of the findings. As it pertains to the process of policy implementation, which entails transforming the objectives of a policy into concrete acts, practices, and regulations, several processes need to be carried out to ensure that the policy is successfully executed and that the desired results are achieved.

6. Conclusions

The objective of the current study was to stress the socioeconomic conditions and the degree of acceptance of innovative tools by end-users (consumers, producers), as well as to develop proposals for public awareness of environmentally safe plant protection tools.

Using microorganisms and molecular tools may raise concerns among the public, similar to those against transgenic and genetically modified organisms.

It was found that consumers' willingness to pay more for food produced using environmentally friendly methods increases with age, length of time working, positive attitudes towards such foods, taste, and labeling of products for the use of environmentally friendly methods, and their perception of farmers' attitudes and knowledge of food safety issues. As for the producers, their decision to use environmentally friendly pesticides (EFP) over conventional ones is determined by demographic characteristics, their perception and interest in the social and environmental impacts of climate change, along with environmental and economic reasons.

On the one hand, consumer viewpoints provide significant insights into how the public perceives and interacts with pest management products. In contrast, producer surveys can provide important information about their preferences, concerns, and perceptions of plant protection tools. Consumer views and preferences are fluid and evolve, influenced by geographic location and personal beliefs. Producers may have different opinions and preferences depending on the crop they grow and the climatic conditions of their region. Hence, comprehensive and objective data analysis from various sources is necessary to derive accurate conclusions about consumer trends and viewpoints on pest control products and broader conclusions about producers' views and preferences on plant protection tools. The above-mentioned results necessitate policy makers to convey sustainability information to consumers in a transparent, evidence-based, and controlled way.

A limitation of this study could be the fact that the survey was conducted only in Greece out of the member project contributors and the small number of farmers that responded to the questionnaires. In the framework of the INTOMED project (intomed.bio.uth.gr), the same survey could be conducted in the participating countries and therefore be the subject of future work. The specific work could unveil similarities and differences among Mediterranean countries concerning the same crops and how different strategies and policy measures adopted could promote sustainable agriculture under the main objective of the Green Deal, which serves as the Bible for the future of agriculture, on the demand side as well as the supply side.

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Appendix A. Demographics of Survey Respondents

Table A1. Demographic profile of consumers.

Profile	Frequencies	Percentage (%)
Gender		
Male	**216**	**44.9**
Female	**244**	**50.7**
Other	**16**	**3.2**

Table A1. *Cont.*

Profile	Frequencies	Percentage (%)
Income Level (Euros per Month)		
<500	**66**	**13.7**
501–1000	**96**	**20.0**
1001–1500	**105**	**21.8**
1501–2000	**98**	**20.4**
2001–2500	**61**	**12.7**
2501–3000	**14**	**2.9**
3001–3500	**17**	**3.5**
3501–4000	**10**	**2.1**
4501–5000	**2**	**0.4**
>5001	**2**	**0.4**
Age		
18–25	**218**	**45.3**
26–35	**88**	**18.3**
36–45	**106**	**22.0**
46–55	**56**	**11.6**
56–65	**9**	**1.9**
Employment Status		
Full-time Employment	**239**	**49.7**
Part-time Employment	**97**	**20.2**
Unemployed	**140**	**29.1**
Household Size		
0	**6**	**1.2**
1	**32**	**6.7**
2	**110**	**22.9**
3	**107**	**22.2**
4	**147**	**30.6**
5	**53**	**11.0**
6	**8**	**1.7**
Number of Children (Under 18)		
0	**281**	**58.4**
1	**69**	**14.3**
2	**72**	**15.0**
3	**5**	**1.0**
Number of Individuals (Over 65)		
0	**357**	**74.2**
1	**51**	**10.6**
2	**8**	**1.7**
3	**2**	**0.4**

Table A1. *Cont.*

Gender	Frequency	Percentage %
Occupation		
Private Employee	**102**	**21.2**
Public Employee	**105**	**21.8**
Self-employed	**45**	**9.4**
Unemployed	**23**	**4.8**
Student/Scholar	**175**	**36.4**
Farmer	**15**	**3.1**
Retired	**7**	**1.5**
Homemaker	**5**	**1.0**
Marital Status		
Married	**156**	**32.4**
Single	**197**	**41.0**
Divorced	**27**	**5.6**
Widowed	**3**	**0.6**
In a Relationship	**93**	**19.3**
Education Level		
Elementary	**9**	**1.9**
Secondary (High School)	**87**	**18.1**
University/Technical School	**266**	**55.3**
Postgraduate	**97**	**20.2**
Other (PhD)	**15**	**3.1**

Table A2. Demographic characteristics of producers.

Gender	Frequency	Percentage %
Male	55	72.4
Female	19	25.0
Age		
18–20	10	13.2
21–29	18	23.7
30–39	19	25.0
40–49	14	18.4
50–59	15	19.7
Education		
Primary School	3	3.9
Secondary School/High School	21	27.6
University/Technical School	31	40.8
Postgraduate/PhD	21	27.6

Table A2. *Cont.*

Gender	Frequency	Percentage %
Marital Status		
Married	55	72.4
Single	3	3.9
Divorced	2	2.6
Widowed	1	1.3
In a Relationship	15	19.7
Household Members		
1	3	3.9
2	17	22.4
3	12	15.8
4	14	18.4
5	13	17.1
6	1	1.3
Annual Income		
<10,000	4	5.3
10,000–20,000	57	75.0
20,001–30,000	7	9.2
>40,000	8	10.5
Production Cost		
<50%	48	63.2
50–80%	23	30.3
80–100%	5	6.6
Cooperative Members		
Yes	29	38.2
No	47	61.8
Other Local Association		
Yes	16	21.1
No	60	78.9

References

1. Pimentel, D. Environmental and Economic Costs of the Application of Pesticides Primarily in the United States. *Environ. Dev. Sustain.* **2005**, *7*, 229–252. [CrossRef]
2. Pretty, J. Agricultural Sustainability: Concepts, Principles and Evidence. *Philos. Trans. R. Soc. B Biol. Sci.* **2008**, *363*, 447–465. [CrossRef] [PubMed]
3. Kitte, J.A. The Impact of Pesticides on Human Health and the Environment. *Environ. Health Perspect.* **2011**, *119*, A296.
4. Kremen, C.; Iles, A.; Bacon, C. Diversified Farming Systems: An Agroecological, Systems-Based Alternative to Modern Industrial Agriculture. *Ecol. Soc.* **2012**, *17*, 4. [CrossRef]
5. Alexoaei, A.P.; Robu, R.G.; Cojanu, V.; Miron, D.; Holobiuc, A.M. Good practices in reforming the common agricultural policy to support the european green Deal—A perspective on the consumption of pesticides and fertilizers. *Amfiteatru Econ.* **2022**, *24*, 525–545. [CrossRef]
6. Stenrød, M.; Lang, K.; Almvik, M.; Holten, R.; Christiansen, A.; Liu, X.; Jing, Q. Food Safety and the Importance of Comprehensive Analytical Methods for Pesticides and Other Contaminants. In *Innovation for Environmentally-Friendly Food Production and Food Safety in China*; Springer Nature Singapore: Singapore, 2023; pp. 27–66.
7. Baker, M.A.; Bunch, J.C.; Kelsey, K.D. An Instrumental Case Study of Effective Science Integration in a Traditional Agricultural Education Program. *J. Agric. Educ.* **2015**, *56*, 221–236. [CrossRef]

8. Acevedo, M.; Pixley, K.; Zinyengere, N.; Meng, S.; Tufan, H.; Cichy, K.; Bizikova, L.; Isaacs, K.; Ghezzi-Kopel, K.; Porciello, J. A Scoping Review of Adoption of Climate-Resilient Crops by Small-Scale Producers in Low- and Middle-Income Countries. *Nat. Plants* **2020**, *6*, 1231–1241. [CrossRef] [PubMed]
9. Fan, S.; Rue, C. *The role of smallholder farms in a changing world. The Role of Smallholder Farms in Food and Nutrition Security*; Springer: Berlin/Heidelberg, Germany, 2020; pp. 13–28. Available online: https://library.oapen.org/bitstream/handle/20.500.12657/39585/1/2020_Book_TheRoleOfSmallholderFarmsInFoo.pdf#page=22 (accessed on 1 July 2023).
10. Saroop, S.; Tamchos, S. Impact of Pesticide Application: Positive and Negative Side. In *Pesticides in a Changing Environment*; Elsevier: Amsterdam, The Netherlands, 2024; pp. 155–178.
11. Suckling, D.M.; Stringer, L.D.; Stephens, A.E.; Woods, B.; Williams, D.G.; Baker, G.; El-Sayed, A.M. From Integrated Pest Management to Integrated Pest Eradication: Technologies and Future Needs. *Pest Manag. Sci.* **2014**, *70*, 179–189. [CrossRef] [PubMed]
12. Dyck, V.A.; Hendrichs, J.; Robinson, A.S. *Sterile Insect Technique: Principles and Practice in Area-Wide Integrated Pest Management*; Taylor & Francis: Oxford, UK, 2021.
13. Grunert, K.G. Food Quality and Safety: Consumer Perception and Demand. *Eur. Rev. Agric. Econ.* **2005**, *32*, 369–391. [CrossRef]
14. Verneau, F.; La Barbera, F.; Furno, M. The role of health information in consumers' willingness to pay for canned crushed tomatoes enriched with Lycopene. *Nutrients* **2019**, *11*, 2173. [CrossRef]
15. Torjusen, H.; Sangstad, L.; O'Doherty Jensen, K.; Kjærnes, U. European Consumers Conceptions of Organic Food: A Review of Available Research. 2004. Available online: https://orgprints.org/id/eprint/2490/ (accessed on 25 June 2024).
16. Hoek, A.C.; Luning, P.A.; Weijzen, P.; Engels, W.; Kok, F.J.; de Graaf, C. Replacement of Meat-by-Meat Substitutes. A Survey on Person- and Product-Related Factors in Consumer Acceptance. *Appetite* **2004**, *42*, 265–272. [CrossRef] [PubMed]
17. Gracia, A.; de-Magistris, T. The Demand for Organic Food in Emerging Markets: The Case of Ecuador. *Food Qual. Prefer.* **2016**, *54*, 167–176.
18. Sampalean, N.I.; Rama, D.; Visent, G. An Investigation into Italian Consumers' Awareness, Perception, Knowledge of European Union Quality Certifications, and Consumption of Agri-Food Products Carrying Those Certifications. *Bio-Based Appl. Econ.* **2021**, *10*, 35–49. [CrossRef]
19. Zarbà, C.; Pappalardo, G.; Selvaggi, R.; Pecorino, B. The EU Agri-Food System in the Recent Crisis Scenarios. *Econ. Agro-Aliment.* **2024**, *25*, 87–107. [CrossRef]
20. Lykogianni, M.; Bempelou, E.; Karamaouna, F.; Aliferis, K.A. Do Pesticides Promote or Hinder Sustainability in Agriculture? The Challenge of Sustainable Use of Pesticides in Modern Agriculture. *Sci. Total Environ.* **2021**, *795*, 148625. [CrossRef] [PubMed]
21. Karunathilake, S.; Yu, J.; Ahmed, S. Impact of Chemical Pesticides on Consumer Health and the Environment: A Critical Review. *Environ. Sci. Pollut. Res.* **2023**, *30*, 4567–4589.
22. Van Bussel, L.M.; Kuijsten, A.; Mars, M.; Van't Veer, P. Consumers' Perceptions on Food-Related Sustainability: A Systematic Review. *J. Clean. Prod.* **2022**, *341*, 130904.
23. Eldesouky, A.; Mesias, F.J.; Escribano, M. Perception of Spanish Consumers towards Environmentally Friendly Labelling in Food. *Int. J. Consum. Stud.* **2020**, *44*, 64–76. [CrossRef]
24. Jaeger, S.R.; Harker, F.R.; Ares, G. Consumer Insights About Sustainable and 'Beyond Organic' Agriculture: A Study of Biodynamics in the United Kingdom, Australia, Singapore, and Germany. *J. Clean. Prod.* **2023**, *401*, 136744. [CrossRef]
25. Tigan, A.; Popescu, R.; Ionescu, A. Organic Alternatives to Chemical Pesticides: A Sustainable Approach to Agriculture. *J. Sustain. Agric.* **2021**, *39*, 210–225.
26. Cooper, J.; Dobson, H. The Benefits of Pesticides to Mankind and the Environment. *Crop Prot.* **2007**, *26*, 1337–1348. [CrossRef]
27. Carvalho, F.P. Agriculture, Pesticides, Food Security, and Food Safety. *Environ. Int.* **2006**, *9*, 685–692. [CrossRef]
28. Sankoh, A.I. An Assessment of Pesticide Use, Contamination and Impact on the Environment and the Health of People in Sierra Leone. Ph.D. Thesis, Lancaster University, Lancaster, UK, 2016.
29. Weng, C.Y.; Black, C. Taiwanese Farm Workers' Pesticide Knowledge, Attitudes, Behaviors and Clothing Practices. *Int. J. Environ. Health Res.* **2015**, *25*, 685–696. [CrossRef] [PubMed]
30. Khan, M.; Damalas, C.A. Farmers' Willingness to Pay for Less Health Risks by Pesticide Use: A Case Study from the Cotton Belt of Punjab, Pakistan. *Sci. Total Environ.* **2015**, *530–531*, 297–303. [CrossRef] [PubMed]
31. Adjrah, Y.; Dovlo, A.; Karou, S.D.; Eklu-Gadegbeku, K.; Agbonon, A.; De Souza, C.; Gbeassor, M. Survey of Pesticide Application on Vegetables in the Littoral Area of Togo. *Ann. Agric. Environ. Med.* **2013**, *20*, 4.
32. Gupta, B.K.; Mishra, B.P.; Singh, V.; Patel, D.; Singh, M.P. Constraints Faced by Vegetable Growers in Adoption of IPM in Bundelkhand Region of Uttar Pradesh. *Indian J. Ext. Educ.* **2020**, *56*, 92–97.
33. Balasha, A.M. Drivers of Integrated Pest Management Adoption among Small-Scale Vegetable Farmers in Lubumbashi, DR Congo. *Am. J. Rural Dev.* **2019**, *7*, 53–59.
34. Creissen, H.E.; Jones, P.J.; Tranter, R.B.; Girling, R.D.; Jess, S.; Burnett, F.J.; Gaffney, M.; Thorne, F.S.; Kildea, S. Identifying the Drivers and Constraints to Adoption of IPM among Arable Farmers in the UK and Ireland. *Pest Manag. Sci.* **2021**, *77*, 4148–4158. [CrossRef]
35. Deguine, J.P.; Aubertot, J.-N.; Flor, R.J.; Lescourret, F.; Wyckhuys, K.A.; Ratnadass, A. Integrated Pest Management: Good Intentions, Hard Realities. A Review. *Agron. Sustain. Dev.* **2021**, *41*, 1–35.

36. Ahire, R.D.; Kapse, P.S.; Deshmukh, P.R. Socioeconomic and Psychological Determinants of Knowledge and Adoption of IPM Technology for Management of White Grub among the Farmers. *Int. J. Curr. Microbiol. App. Sci.* **2018**, *7*, 1201–1206. [CrossRef]
37. Ghane, F.; Samah, B.A.; Ahmad, A.; Idris, K. The Role of Social Influence and Innovation Characteristics in the Adoption of Integrated Pest Management (IPM) Practices by Paddy Farmers in Iran. *Int. Conf. Soc. Sci. Humanit.* **2011**, *5*, 217–220.
38. Parsa, S.; Morse, S.; Bonifacio, A.; Chancellor, T.C.B.; Condori, B.; Crespo-Pérez, V.; Hobbs, S.L.A.; Kroschel, J.; Ba, M.N.; Rebaudo, F.; et al. Obstacles to Integrated Pest Management Adoption in Developing Countries. *Proc. Natl. Acad. Sci. USA* **2014**, *111*, 3889–3894. [CrossRef] [PubMed]
39. Cameron, P.J. Factors Influencing the Development of Integrated Pest Management (IPM) in Selected Vegetable Crops: A Review. *N. Z. J. Crop Hortic. Sci.* **2007**, *35*, 365–384. [CrossRef]
40. Damalas, C.A.; Georgiou, E.B.; Theodorou, M.G. Pesticide Use and Safety Practices among Greek Tobacco Farmers: A Survey. *Int. J. Environ. Health Res.* **2006**, *16*, 339–348. [CrossRef] [PubMed]
41. Zadjali, S.A.; Morse, S.; Chenoweth, J.; Deadman, M. Factors Determining Pesticide Use Practices by Farmers in the Sultanate of Oman. *Sci. Total Environ.* **2014**, *476–477*, 505–512. [CrossRef] [PubMed]
42. Hashemi, S.M.; Damalas, A.C. Farmers' Perceptions of Pesticide Efficacy: Reflections on the Importance of Pest Management Practices Adoption. *J. Sustain. Agric.* **2010**, *35*, 69–85. [CrossRef]
43. Hashemi, S.M.; Rostami, R.; Hashemi, M.K.; Damalas, A.C. Pesticide Use and Risk Perceptions Among Farmers in Southwest Iran. *Hum. Ecol. Risk Assess.* **2012**, *18*, 456–470. [CrossRef]
44. Karunamoorthi, K.; Mohammed, M. Knowledge and Practices of Farmers With Reference to Pesticide Management: Implications on Human Health. *Arch. Environ. Occup. Health* **2012**, *67*, 109–116. [CrossRef] [PubMed]
45. Mohanty, M.K.; Behera, B.K.; Jena, S.K.; Srikanth, S.; Mogane, C.; Samal, S.; Behera, A.A. Knowledge Attitude and Practice of Pesticide Use Among Agricultural Workers in Puducherry, South India. *J. Forensic Leg. Med.* **2013**, *20*, 1028–1031. [CrossRef]
46. Sharma, R.; Peshin, R.; Shankar, U.; Kaul, V.; Sharma, S. Impact Evaluation Indicators of an Integrated Pest Management Program in Vegetable Crops in the Subtropical Region of Jammu and Kashmir, India. *Crop Prot.* **2015**, *67*, 191–199. [CrossRef]
47. Aertsens, J.; Verbeke, W.; Mondelaers, K.; Van Huylenbroeck, G. Personal Determinants of Organic Food Consumption: A Review. *Br. Food J.* **2009**, *111*, 1140–1167. [CrossRef]
48. Batte, M.T.; Darby, K.; Ernst, S.; Roe, B. Willingness to Pay for Locally Produced Foods: A Customer Intercept Study of Direct Market and Grocery Store Shoppers. In Proceedings of the American Agricultural Economics Association Annual Meeting, Long Beach, CA, USA, 23–26 July 2006.
49. Brown, C. Consumers' Preferences for Locally Produced Food: A Study in Southeast Missouri. *Am. J. Altern. Agric.* **2003**, *18*, 4. [CrossRef]
50. Hayati, B.; Haghjou, M.; Pishbahar, E. Effecting Factors on Consumers' Willingness to Pay a Premium for Pesticide-Free Fruit and Vegetables in Iran. *MOJ Food Process Technol.* **2017**, *4*, 137–145. [CrossRef]
51. Pool, W.M. The Influences of Consumer Attitudes and Perceptions about Pesticides and Produce Quality on Technology Transfer. Maters's Thesis, Rochester Institute of Technology, Rochester, NY, USA, 1996. Available online: https://repository.rit.edu/theses/428/ (accessed on 22 May 2024).
52. Kawemama, W.; Mugula, J.; Wostry, A. Factors Affecting Consumers' Choice in Consumption of Organic Vegetables and Methods Used to Avoid Consumption of Unhealthy Foods in Tanzania. *Int. J. Nutr. Food Sci.* **2018**, *7*, 71–80. [CrossRef]
53. Mertler, C.A.; Vannatta, R.A.; LaVenia, K.N. *Advanced and Multivariate Statistical Methods: Practical Application and Interpretation*; Routledge: London, UK, 2021.
54. Halkias, G.; Davvetas, V.; Diamantopoulos, A. The interplay between country stereotypes and perceived brand globalness/localness as drivers of brand preference. *J. Bus. Res.* **2016**, *69*, 3621–3628. [CrossRef]
55. Robin, D.C.; Marchand, P.A. Expansion of the low-risk substances in the framework of the European pesticide regulation (EC) No 1107/2009. *Eur. J. Risk Regul.* **2022**, *13*, 514–531. [CrossRef]
56. Wolff, L. Regulating pests—Material politics and calculation in integrated pest management. *Environ. Plan. E Nat. Space* **2023**, *6*, 455–472. [CrossRef]
57. Rahman, S. Agroecological, Climatic, Land Elevation and Socioeconomic Determinants of Pesticide Use at the Farm Level in Bangladesh. *Agric. Ecosyst. Environ.* **2015**, *212*, 187–197. [CrossRef]
58. Antonious, G.F. Pesticides: Types, Uses, and Impact on Environment. In *Integrated Pest Management and Pest Control-Current and Future Tactics*; InTech: Houston, TX, USA, 2005; pp. 87–116.
59. Dhananjayan, V.; Ravichandran, B. Occupational Health Risk of Farmers Exposed to Pesticides in Agricultural Activities. *Curr. Opin. Environ. Sci. Health* **2018**, *4*, 31–37. [CrossRef]
60. Mubushar, M.; Aldosari, F.O.; Baig, M.B.; Alotaibi, B.M.; Khan, A.Q. Assessment of Farmers on Their Knowledge Regarding Pesticide Usage and Biosafety. *Saudi J. Biol. Sci.* **2019**, *26*, 1903–1910. [CrossRef]

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Are South Korea's Environmental Policies Rational? An Analysis Focusing on Fine Dust Programs in the Seoul Metropolitan Area

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Abstract: Since 2018, the government of South Korea has strengthened its environmental policies to solve the problem of fine particulate matter in the air. Because of these strict regulations, diesel cars have been replaced with cleaner vehicles, and coal power plants have been shut down. Despite these government efforts, some researchers assert that fine dust programs have failed in Seoul, the capital of Korea. In other words, they conclude that the central and local governments designed and implemented the policies unreasonably. Despite these critics, this study attempts to prove that the government has thoroughly and meticulously prepared its policies on fine particles. Also, it tries to demonstrate that the policy scheme has been properly established. To attain these research goals, the theory of procedural rationality is adopted and utilized. As a result of the analysis, six steps of procedural rationality were identified in the Korean policy on fine dust: problem identification, goal setting, searching for alternatives, consequence prediction, comparison of alternatives, and policy decision. In conclusion, this study provides suggestions for environmental policies in other metropolitan cities, especially in developing countries that suffer from severe air pollution.

Keywords: procedural rationality; environmental Kuznets curve; path dependency; air pollution; fine dust

1. Introduction: A New Environmental Challenge of Fine Dust

South Korea has achieved rapid economic growth since the 1970s. As a side effect of material prosperity, it has experienced environmental pollution in advance of other developing countries such as Brazil, India, and China. However, the Korean government has dealt with its environmental problems effectively. These ecological outcomes could be explained by the hypothesis of the Environmental Kuznets Curve, which shows the relationship between economic growth and environmental degradation [1]. In brief, developing countries can improve their environmental quality after passing a specific turning point of economic income. Generally, the turning point of the per capita annual income is estimated at approximately USD 10,000 according to Grossman and Krueger (1995). In fact, the air and water quality of South Korea has improved since the 1990s [2]. Specifically, Jiang et al. (2020) identified an inverted U-shaped pattern with regard to air pollution in South Korea [3]. Likewise, Choi et al. (2015) showed that there was a significant improvement in the country's water quality, and proved that economic growth accompanied a shift in environmental policy [4].

In spite of these positive outcomes, Koreans have a serious concern about the air pollution issue, especially about fine particulate matter. Kwag et al. (2021) reported that fine particulate matter became severe from 2010 to 2016 [5]. Therefore, emission control policies regarding fine dust have been introduced and executed to solve the air pollution problem [6]. Nevertheless, the government was alarmed that the level of ultra-fine dust exceeded environmental standards several times in 2018. Consequently, Koreans had to wear face masks to prevent inhaling fine particles. To make things worse, this issue provoked an international conflict, because the considerable amount of ultra-fine dust is regarded to have originated from China and moved to South Korea.

In addition, the problem of fine particulate matter has developed into a domestic political agenda in South Korea. For instance, Moon Jae-in, who was inaugurated as president in 2017, suggested aggressive policies to reduce the concentration level of ultra-fine dust as a presidential election pledge. As explained above, even though South Korea had shown positive performances in some environmental areas, it was still experiencing serious air quality degradation, especially with regard to fine particles [7].

In this context, where the policy of fine dust has become a critical issue at home and overseas, it is necessary for scholars to provide scientific research results because policies, fundamentally, are outcomes of political science. However, there have only been political controversies regarding fine dust issues in the Seoul Metropolitan Area, South Korea. Therefore, this study attempts to scientifically analyze the environmental policies on fine particulate matter from the viewpoint of *procedural rationality*. To attain these research goals, this study consists of five sections. In the following Section 2, the Korean policies on fine dust are described in outline. The basic theory of procedural rationality is illustrated in Section 3. Then, Section 4 analyzes the policy process of fine particles in the Seoul Metropolitan Area. In conclusion, Section 5 summarizes research results and suggests policy implications.

2. Literature Review of Korean Policies on Particulate Matter

2.1. Fine Dust Policies in South Korea

Air pollution has been a major field of environmental policies in South Korea, like in other industrialized countries. For instance, London smog is a well-known historical case of atmospheric pollution, induced by coal combustion in the 1950s, and Los Angeles also suffered from similar air pollution caused by vehicular emissions until the 1990s. Likewise, the Korean government has strengthened the standard of air quality and made strict policies since the 2000s [8].

In 2003, the central government of South Korea enacted the *Special Act on the Improvement of Air Quality in Seoul Metropolitan Area* and commenced enforcement of this Act in 2005. This was established because the capital city had faced a new kind of air pollution, fine particulate matter, unlike traditional pollutants such as sulfur oxides and nitrogen dioxide. Since then, fine dust has become a serious problem in this country. Based on this act, the *First Seoul Metropolitan Air Quality Control Master Plan* was established in 2005. The major implementation measures are illustrated in Table 1. From then on, South Korea was able to formulate a systematic policy scheme to solve the problem of fine dust [9].

Table 1. Implementation measures of the first master plan for metropolitan air quality management.

Control measures for mobile, on-road sources	
○	Newly manufactured vehicles
	· Strengthening emission standards in accordance with the EU standards
	· Improving the supply of low-emission vehicles
○	In-use vehicles
	· Installing emission reduction equipment, retrofitting with cleaner engines, etc.
	· Promoting vehicle inspection systems, strengthening education, etc.
Control measures for stationary sources	
○	Large-sized enterprises
	· Establishing annual allowable emission loads, an emissions trading system, etc.
○	Small and medium-sized enterprises
	· Strengthening emission standards in accordance with those of developed countries
	· Managing small incinerators, reducing volatile organic compounds, etc.
	· Installing efficient burners, providing technological assistance, etc.

Table 1. *Cont.*

Environmentally friendly energy and city management
· Establishing community energy supply systems, supplying low-sulfur and clean fuels, etc.
· Conducting air quality management through wind passages, etc.

Source: [10].

Hereafter, the Korean government endeavored to reduce the concentration of fine dust (particulate matter, PM). For instance, the concentration of PM_{10}, a relatively large fine dust of which the diameter is around 10 μm, was 69 $\mu g/m^3$ at that time, and the government set the ambitious goal of reducing this to 40 $\mu g/m^3$, which was the same target level of the neighboring capital city, Tokyo in Japan. However, these policies were just focused on PM_{10}. In other words, the Korean policy had limitations as it did not consider $PM_{2.5}$, an ultra-fine dust of which the diameter is about 2.5 μm [11].

After ten years of the first master plan, the government presented the second master plan in 2013. This plan emphasized human health risks from air pollution and introduced a standard for $PM_{2.5}$. In addition, the central government adopted new policy measures such as environmentally friendly power generation, industrial complexes with low emissions, the expansion of infrastructure for mass transportation, and so forth. Table 2 illustrates these new policy measures. Municipalities such as Seoul and Incheon followed the policy direction and cooperated with the central government [12].

Table 2. Comprehensive measures for fine dust management in Korea.

Sector	Details
Power generation	· Reviewing small coal-fired power plants · Shutting down old power plants in spring · Expansion of renewable energy to 20% in 2030
Industry	· Implementation of a total dust control system · Establishment of a nitrogen oxide discharge fee · Expansion of total management
Transport	· Expansion of the supply of eco-friendly cars · Strengthening of vessel and port management · Expansion of low-emission construction machinery · Strengthening of motorcycle management · Expansion of auto-restricted zones
Sensitive layer	· Advancement of fine dust environmental standards · Establishment of standards for fine dust in the sensitive layer · Expansion of measurement networks near education facilities · Establishment of indoor sports facilities · Conversion of children's commuting vehicles to eco-friendly vehicles · Care services for sensitive families · Designation of "clean zones" in relation to fine dust
International cooperation	· Korea and China summits · Positive consideration of international agreements

Source: [9].

In 2019, the administration of Jae-in Moon launched the *National Council on Climate and Air Quality (NCCA)*, a new official control tower for fine dust. Ban Ki-moon, the former UN Secretary-General, was appointed as the chairperson of the NCCA to induce international cooperation with neighboring countries, including China. The most prominent feature of this council is the attendance of all the stakeholders such as experts, government officials, politicians, civic groups, and even ordinary citizens. In 2020, the council proposed a stern regulation of "*No diesel vehicle sales by 2035*".

2.2. Results of the Policies

Owing to these aggressive responses, the air quality was improved nationwide and locally. In detail, the standard had been strengthened in 2006, and the goal of PM_{10} was achieved in 2011. Figure 1 shows the time-series changes in the PM_{10} concentration. Namely, national and local air quality was improved below the standard after the implementation of related policies for five years. However, ultra-fine dust pollution did not improve regardless of the new policies added in the second master plan. In other words, there had been no distinguished accomplishment, as seen in Figure 2. However, the Ministry of Environment decided to reinforce the standard of $PM_{2.5}$ from 25 $\mu g/m^3$ to 15 $\mu g/m^3$ in 2015, although the performance was not satisfactory. From then on, ordinary citizens began to notice that they were living in bad air conditions and started to buy air purifiers and face masks. Consequently, air pollution has become a tangible concern since then [8].

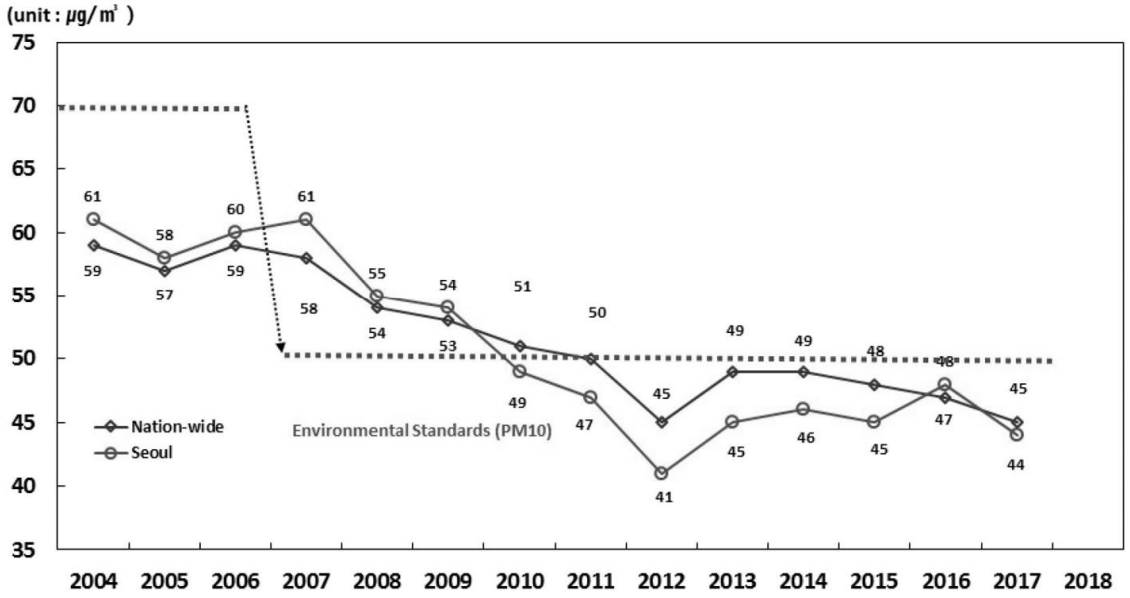


Figure 1. Concentration level of PM_{10} in South Korea. Source: [8].

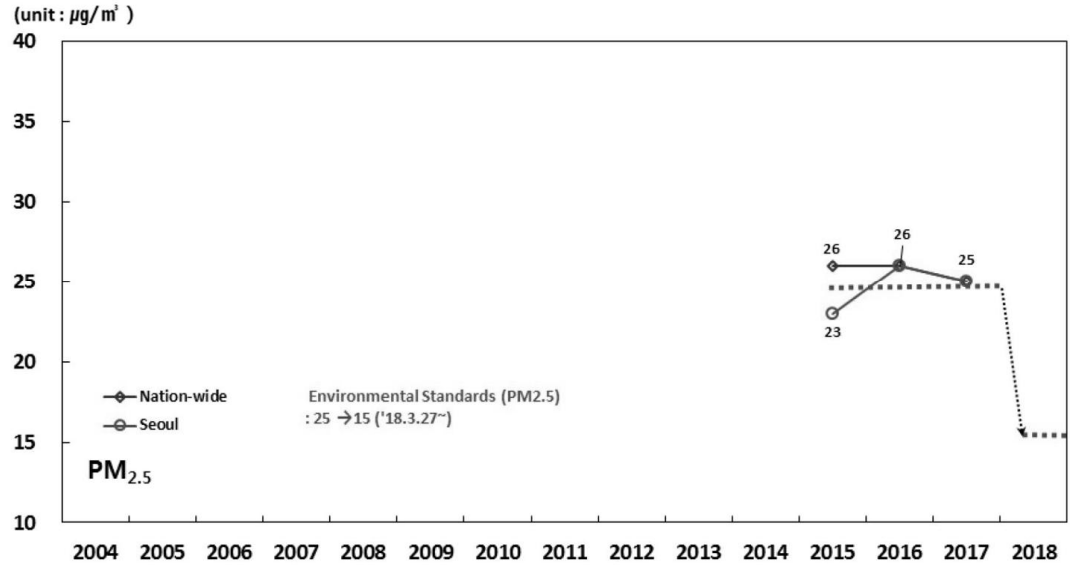


Figure 2. Concentration level of $PM_{2.5}$ in South Korea. Source: [8].

In this situation, Kim and Lee (2019) diagnosed the effectiveness of fine dust policies and concluded that the programs of local governments did not work properly [13]. For

example, while Seoul introduced free-riding programs for mass transportation in case of air pollution emergencies, these policies did not show the desired outcomes. Moreover, Choi and Kim (2016) insisted that it was inevitable for these programs to fail because of path dependency, which is a branch of irrational decision-making theory [14]. In other words, they concluded that the Korean policy on fine particles had been locked in the existing path of institutions and policies despite government efforts.

On the contrary, this study attempts to prove that the ultra-fine dust policy of Korea was relatively rational and reasonably well designed. However, in order to attain these research goals, it is necessary to narrow down the research topic. Therefore, the policy on fine dust equivalent to PM_{10} will be excluded, and it will focus on $PM_{2.5}$ only. This is because the ultra-fine dust policy is more important in the viewpoint of its timeliness and seriousness. In fact, $PM_{2.5}$ is related to lung cancers and the WHO has regarded it as a carcinogen since 2013. With this clarified and confined range of the research target, this study will analyze the process of the environmental policy on ultra-fine dust by adopting a *Procedural Rationality Model*. The following section, Section 3, will elaborate on basic theories about this rational model. In addition, the distinguishing features of this rational model in comparison to irrational models will be illustrated.

3. Methodology and Analysis Framework of Procedural Rationality

3.1. Irrational Decision-Making Theories

Policy-making procedures can be explained from two different viewpoints: the rational and the irrational models. First, some scholars insist that policy processes are irrational because policies are just the results of politics. Actually, public policies are designed, introduced, and developed by politicians. In this decision-making procedure, the power strength of advocacy groups determines their preferred policy. Consequently, policies are obliged to be irrational as the procedures are influenced by political powers [15].

One of the most famous irrational models for interpreting policy processes is the *Garbage Can Model*. This model was coined by Cohen, March, and Olsen in 1972 [16]. After analyzing decision-making procedures in the United States, they suggested the new concept of *organized anarchy*. Particularly, in some specific organizations such as parliaments and universities, these irrational traits were easily identified.

Concretely, they conceptualized this model as a garbage can that was full of agendas, problems, and issues with regard to public policy. In actuality, representatives in national parliaments tend to accumulate and delay bills submitted by ruling and opposition parties. However, these bills are finally passed within a package deal at some point, without a reasonable explanation. Like this, political decision-making is not rational, and policy is regarded as a product of a power game in this model.

In detail, the Garbage Can Model consists of social problems, participants, choice opportunities, and solutions for decision-making. Namely, these components are factors of organized anarchy. Additionally, Cohen et al. (1972) suggested three preconditions for applying the Garbage Can Model: problematic preference, unclear causality, and arbitrary participation [15]. To summarize, participants are not responsible for their attendance, the preference of decision-makers is disordered, and the causal relationship between policy goals and means is ambiguous in this irrational model.

Afterward, the *Policy Stream Model* was developed from the Garbage Can Model by John Kingdon in 1984. Because of this theoretical background, the Policy Stream Model is inevitably another irrational model for explaining policy processes from the viewpoint of politics. However, this model provides a more elaborate framework for policy analysis. Specifically, Kingdon (1984) illustrated that policy issues attain official agenda status, and solutions are chosen by decision-makers in the public sphere [17]. Currently, this model is also called the policy streams framework, the multiple streams model, or the multiple streams approach [18–20].

This model assumes that there are three independent streams in the policy process: a problem stream, a policy stream, and a political stream [21]. First, the problem stream

contains the conditions and components of a specific issue. At a particular moment, these conditions come to the attention of decision-makers [22]. Second, the policy stream is related to alternative solutions to the problem. Kingdon described that solution ideas float around in a primeval policy soup [23]. Third, the political stream encompasses national moods, public opinion, and power dynamics. This stream naturally influences the receptiveness of voters to certain solutions [24].

In this Policy Stream Model, the meaningful point is the concept of policy windows, which is improved from the original Garbage Can Model. In short, as the three streams align by chance, policy windows are open for the establishment of new policies. Therefore, policy windows provide for the possibility of policy changes [19]. However, the periods of window opening are so short that policy entrepreneurs should actively attempt to introduce their preferred policies [25].

Until now, a number of scholars have shown an interest in this attractive model and utilized it to analyze social phenomena. Since 1984, hundreds of studies have cited Kingdon's article and applied the Policy Stream Model in their analyses. Rawat and Morris (2016) illustrate this trend, reporting a peak in citations of Kingdon's article during the mid-1990s and a downturn afterward. In this descending period, some researchers identified limitations in the Policy Stream Model [26]. For instance, defects in policy entrepreneurs were pointed out by American scholars. Also, developing countries are known to have different policy streams. Despite these critics and the down-turning tendency of citations, the Policy Stream Model is still an influential theory in social sciences. For example, Kagan (2019) adopted the multiple streams model to the policy of a renewable energy portfolio standard in Hawaii, and Huber-Stearns et al. (2019) analyzed a case of institutional innovation in forest watershed governance using a multiple streams approach [23,27].

3.2. Rational Decision-Making Theories

The above sub-section has outlined the history of irrational decision-making theories and briefly introduced a couple of major models. In this part, the opposite viewpoint will be delineated: a *Procedural Rationality Model* for policy processes. Rationality is definitely a very ambiguous notion in the fields of philosophy and cognitive psychology. In fact, there have been theoretical controversies about whether rationality can be reliably defined or not [28]. In contrast, there are overall agreements about rationality among social scientists. In the mid-1950s, Herbert Simon conceptualized procedural rationality to understand how public choices are made by governments [29]. Thereafter, rationality in policy processes has been defined as a series of reasonable and logical decision-making [30].

This rational policy-making process consists of six steps: problem identification, goal setting, searching for alternatives, consequence prediction, comparison of alternatives, and policy decision. First, public policies certainly start from social problems because governments are the only authorities that ought to solve their public issues by using policies. Therefore, *problem identification* is the first step of policy processes. In this step, the identification is characterized by the objectivity of problems and the subjectivity of their definitions. Second, policy goals are set after identifying social problems. In this step of *goal setting*, the intent of policies is classified as either remediation or creativity. Also, the desirability of the goal can be evaluated using criteria such as appropriateness and adequacy. Third, governments need to search for instruments to attain policy goals. In this step of *searching for alternatives*, policy instruments are derived from experiences, theories, experts, and stakeholders. Fourth, the next step is *consequence prediction*. After exploring policy instruments, the results of individual alternatives should be anticipated using experimentation, modeling, and intuition. Fifth, a *comparison of alternatives* is necessary before the final decision-making. In this step, effectiveness, efficiency, equity, and feasibility can be adopted as criteria for assessment. Sixth, *policy decision* is the last step. Through this, an optimal policy alternative can be finally chosen [31].

This study utilizes these six steps for analyzing the procedural rationality of the Korean policies on fine particulate matter. Namely, if the procedure of policy-making in South

Korea followed these steps properly, the policy processes could be regarded to be rational. In contrast, if the Korean government did not adopt these six steps in general, the fine dust policy of the country would be judged to be irrational. Figure 3 schematizes a framework for the analysis of procedural rationality [28].

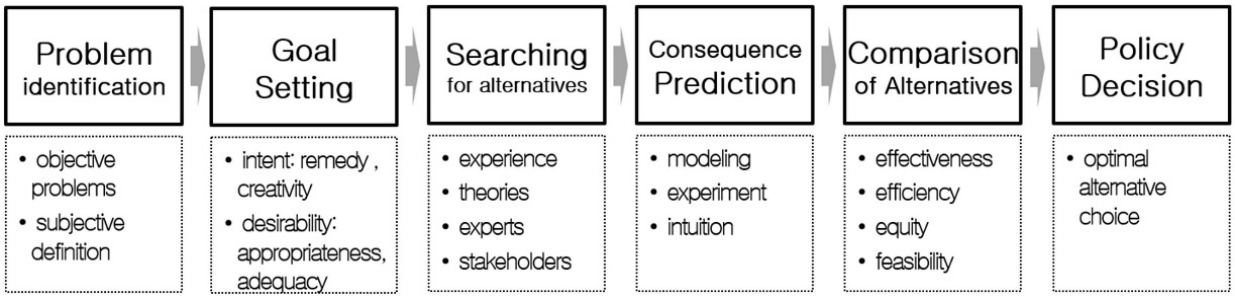


Figure 3. Analysis framework for evaluating procedural rationality.

Before utilizing this analytic framework, it is necessary to narrow down and confirm the scope of this study. First, the scope of contents is restricted to fine particulate matter, especially ultra-fine dust ($PM_{2.5}$). Second, the scope of time corresponds to the period from 2013 to 2020, as illustrated in Section 2. Third, the scope of methodologies is limited to procedural rationality, not substantial rationality. In the next section, the analysis framework will be applied within these research scopes.

4. Analysis and Results

4.1. Problem Identification

Governments always encounter plenty of social problems. Among these, only a few issues are chosen as worthwhile policy agendas. When selecting issues, public administrations consider two priorities, namely the objectivity of the problems and the subjectivity of their definitions. Firstly, with regard to fine particulate matter in South Korea, there was an *objectively identified problem* in 2019. The annual mean concentration of $PM_{2.5}$ in Seoul was 24.8 $\mu g/m^3$, which was significantly higher than 10 $\mu g/m^3$, the target of the World Health Organization [32]. The international organization suggested four targets of $PM_{2.5}$ in its report entitled "*Air quality guidelines for particulate matter, ozone, nitrogen dioxide, and sulfur dioxide*" [33]. In detail, Interim Targets 1, 2, 3, and the Air Quality Guideline are 35, 25, 15, and 10 $\mu g/m^3$, respectively. Among these, the Korean government adopted the level of Interim Target 2 as a national standard in 2013. Furthermore, the IARC (International Agency for Research on Cancer), an affiliated sub-organization of the WHO, announced in the same year that ambient fine particulate matter ($PM_{2.5}$) was included as a carcinogen that provokes lung cancers [34]. Thereafter, the Ministry of Environment in South Korea strengthened the standard of $PM_{2.5}$ to 15 $\mu g/m^3$ in accordance with Interim Target 3 in 2015. As shown in this case, there was indisputable air pollution in Korea with respect to ultra-fine dust, including $PM_{2.5}$.

Secondly, policy-making processes need their own *subjective definition*. If a majority of Koreans have no interest in environmental pollution and ignore the issue of fine particles, politicians would not legislate any related bills and not allocate budgets at all. However, Korean voters were very sensitive to the issue of air pollution. Figure 4 indicates the number of articles on fine dust and ultra-fine dust in newspapers from 2011 to 2017. Namely, right after the two announcements from the Ministry of Environment in 2013 and 2015, Korean citizens revealed enormous concerns about PM_{10} and $PM_{2.5}$. Owing to this large interest from the public, government officials and politicians were able to enact and revise the law on fine particulate matter [35]. Therefore, with regard to problem identification, there were two fulfilled conditions: objective problems and subjective definitions.

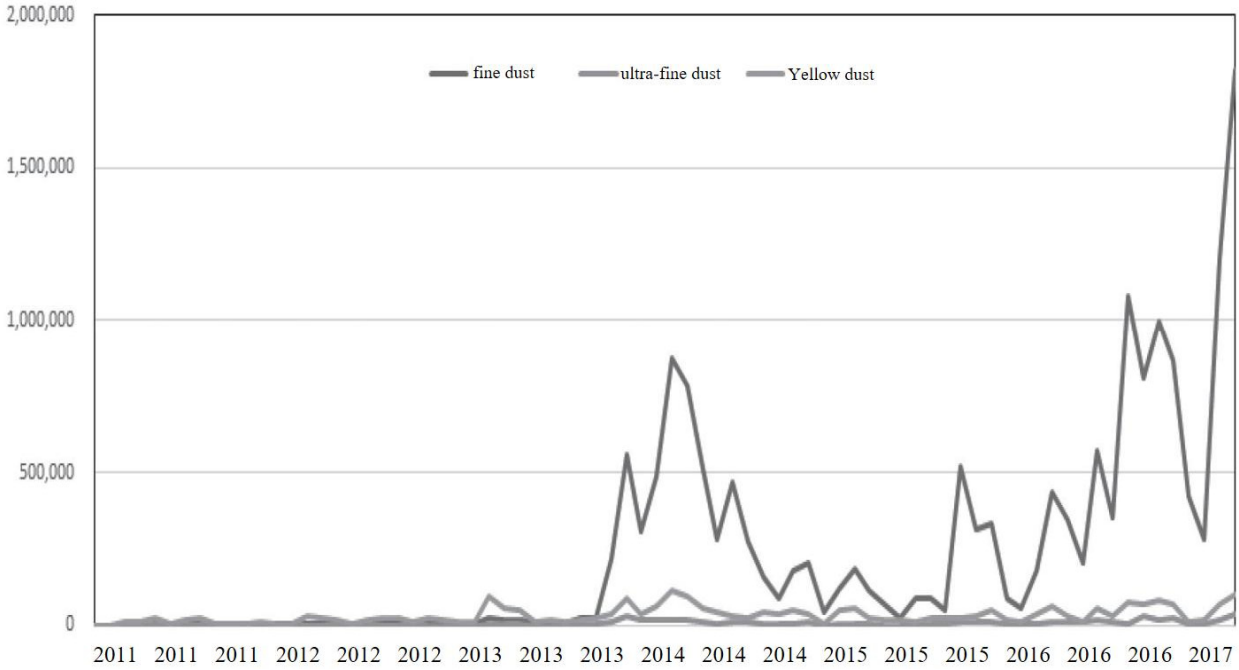


Figure 4. The number of articles on fine dust and ultra-fine dust. Source: [35].

4.2. Goal Setting

In the next step, it is necessary to distinguish between the two *intents of policy*: remediation or creativity. Here, creative goals are targets that have not been encountered previously. As times are rapidly changing in this day and age, governments should follow trends and adapt to a new transition. For example, public administrations could aim to make a new future, such as the era of artificial intelligence or the fourth industrial revolution. However, the goals of environmental policies, including fine dust programs, are not creative at all.

In contrast, the policy goals regarding fine particulate matter are a sort of remedy. Surely, there had rarely been air pollution before industrialization. In fact, fine particles mostly originate from two major sources: coal-fired power plants and internal combustion engines. In the Seoul Metropolitan Area, the visibility impairment problem originating from fine particulate matter has received considerable attention [36]. Consequently, the purpose of the policies was to restore the air quality from polluted to clean. Therefore, the type of policy goals for ultra-fine dust could be classified as a remedy.

In this step of goal setting, it is also necessary to examine the *desirability* of the policy. The generally accepted definition of public policy is the effort of governments to attain desirable societies. Here, policy goals are related and indispensable to the desired state. Concretely, desirability is divided into two sub-components: appropriateness and adequacy. These two desirability components regarding ultra-fine particles were enunciated in the government report entitled the *Comprehensive Plan on Fine Dust Management* [37].

First, the policy goal of fine particulate matter was appropriate because clean air is a prerequisite for a healthy life. As illustrated in Section 1, air pollution has been the most serious anxiety for Korean citizens. Therefore, reducing the $PM_{2.5}$ concentration as a policy goal was obviously desirable. Second, the policy goal of eliminating fine particles was also adequate. After the Ministry of Environment set the target concentration at 25 $\mu g/m^3$ in 2013, the government strengthened this standard again up to 15 $\mu g/m^3$ in 2015, only two years after the first announcement. According to the official report, the *Comprehensive Plan on Fine Dust Management*, the ministry anticipated that this target was achievable [38].

4.3. Searching for Alternatives

After setting policy goals, governments should search for feasible means to achieve the goals. It is widely accepted that there are four major sources for policy alternatives:

experiences, theories, experts, and stakeholders. First, the Korean government had already acquired *experiences* from itself and others. In 2016, the United Nations Environment Programme published a report on air pollution policies and programs around the world [38]. Other countries' policies and practices in this report were exemplary of the Korean fine dust policy. Particularly, South Korea referred to the experience of the United States because it has strong autonomy at the level of municipalities in the field of air pollution policies related to fine particles [39]. Additionally, previous domestic policies about PM_{10} in the *First Seoul Metropolitan Air Quality Control Master Plan*, illustrated in Section 2, were also helpful and beneficial to the ultra-fine dust policy [40].

Moreover, the ministry utilized *theories* and *experts* from the national research institute, the Korea Environment Institute, to obtain policy alternatives. This institute was first established as the Korea Environmental Technology Research Institute in 1992, and the current name was approved in 1997. Currently, it has 224 staff, including 140 experts. In particular, this institute specializes in supporting environmental policies on behalf of the government, and the personnel consists of scientists, engineers, economists, and so forth.

Actually, the institute analyzed policy alternatives by using theories and scientific models, and two research reports were published. In the first report, the physical characteristics of $PM_{2.5}$ were examined, the health impacts of fine particulate matter were estimated, and a roadmap for management programs was designed [41]. The second report formulated fine dust policies at the level of municipalities, particularly in industrial and residential cities such as Ulsan, Gwangju, and Daejeon [42].

Also, the Ministry of Environment held two official conferences in 2014 and 2016 to collect policy alternatives from *stakeholders* including private companies, civil activists, and local residents. Their suggestions were reflected in government policies. In addition, this open-to-the-public policy process was able to strengthen social trust between the government and private sectors. Consequently, this sort of partnership was helpful in achieving effective implementation [43].

4.4. Consequence Prediction

After collecting policy alternatives from various sources, governments need to predict the consequences of individual policy means. At this step, experts utilize modeling methods, scientific experiments, and their intuitions. First, researchers applied *atmospheric models* to simulate the behavior of pollutants in the air. To obtain more accurate results, they had to collaborate with Chinese experts because fine dust is a transboundary pollutant. However, Chinese authorities were initially not cooperative because the government denied its responsibility. Therefore, South Korea alternatively looked for joint research with the United States. Finally, the Chinese government decided to collaborate, and the North-East Asia Clean Air Partnership was launched in 2018. Other international channels such as the Tripartite Environmental Ministers Meeting and Tripartite Policy Dialogue on Air Pollution were also activated. Owing to this multilateral partnership, Korean and Chinese researchers were able to develop simulation models for fine dust in conjunction [8].

Additionally, *artificial rain experiments* were conducted 29 times from 2016 to 2018 in the metropolitan area, and one experiment was implemented in 2019 over the Yellow Sea. The purpose of these numerous experiments was to identify whether artificial rain could eliminate fine dust or not. Approximately half of the total amount of fine particles was presumed to originate from China. Therefore, if the Korean government could remove fine dust over the sea, air pollution could be eased in Seoul and across the Korean peninsula. However, the effect of the experiments was negligible, disappointing the Ministry of Environment. Consequently, the government excluded artificial rain from potential policy alternatives [44].

The ministry also utilized experts' *intuitions*. In some circumstances, governments are inevitably dependent on specialists because computer models cannot perfectly predict the future. Therefore, professional intuitions from experts could be the only method to rely on for anticipation. Actually, the Korean government listened attentively to opinions from

domestic and foreign experts. This was because the fine dust issue is not restricted to South Korea but also involves neighboring countries. In this complicated international situation, experts' intuitions had the potential to be especially valuable.

4.5. Comparison of Alternatives

The next step after predicting consequences involves a comparison of alternatives. In the previous step, the environmental impacts, technical possibilities, and economic costs of potential policy alternatives are estimated. Then, governments need to compare individual alternatives before finally deciding on policy means. In this step, criteria such as effectiveness, efficiency, equity, and feasibility could be utilized.

Among these, *effectiveness* is a basic criterion with regard to public policy. Indeed, in the *Comprehensive Plan on Fine Dust Management*, the government considered whether individual fine dust programs could attain the policy goals or not [34]. Subsequently, it is necessary to examine *efficiency* because governments always have financial constraints. In South Korea, the Ministry of Economy and Finance participated in the comprehensive plan and reviewed costs and budgets. If there had been no agreements from the financial ministry, the plan for fine particles would not have been confirmed. Additionally, the Korean government took *equity* into account. As seen in Figure 5, the comprehensive plan included considerate and meticulous protection of vulnerable groups such as infants, elderly people, and disabled people. At last, *feasibility* was also reviewed thoroughly. For example, other ministries such as MOTIE (the Ministry of Trade, Industry, and Energy) and MOLIT (the Ministry of Land, Infrastructure, and Transportation) participated in and were associated with achieving the policy goals regarding fine dust.

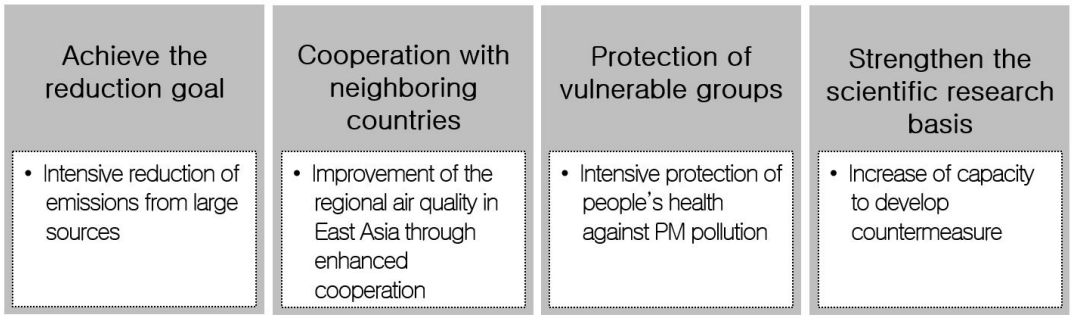


Figure 5. Strategic process in the *Comprehensive Plan on Fine Dust Management*. Source: [37].

4.6. Policy Decision

Based on the comparison of alternatives, governments decide on the optimal policy. With respect to the ultra-fine dust of $PM_{2.5}$ in South Korea, there were two major decisions. Of course, there were other related policies in advance of these two decisions. For instance, the *Special Act on the Improvement of Air Quality in Seoul Metropolitan Area* was introduced in 2003. Owing to this act, the *First Seoul Metropolitan Air Quality Control Master Plan* was also able to be established, as illustrated in Section 2. Nevertheless, the first master plan just focused on relatively large fine dust (PM_{10}) and did not include any regulations concerning ultra-fine particles ($PM_{2.5}$). As the main topic of this study is only $PM_{2.5}$, subsequent policies are more important with regard to fine particulate matter. Therefore, only the two recent policy decisions in 2013 and 2018 are considered in this step.

At first, the *Second Seoul Metropolitan Air Quality Control Master Plan* was declared in 2013, and the Korean government focused on ultra-fine particles and commenced controlling the emission of $PM_{2.5}$ in earnest. In 2018, the *Special Act on the Reduction and Management of Fine Dust* was enacted apart from other existing ordinances. This act empowered the government to solve the problem of ultra-fine dust more effectively. As indicated in Figure 6, the government additionally applied stricter guidelines for $PM_{2.5}$ based on this act. Consequently, Korean citizens began to directly experience stern regulations even in their everyday lives. Actually, a recent press release from the Ministry of Environment

shows that the concentration of fine dust recorded its lowest level, 21.0 μg/m^3, in April 2024, while it was 24.4 μg/m^3 in April 2019 when the regulation started. The ministry insisted that this improvement meant that the environmental policy was effective.

(1) Vision		
Toward Clean Air and Blue Skies in Korea		
(2) Goal		
Thirty-percent reduction in domestic emissions by 2020		
(3) Project Focus		
Reductions in Local Emissions	1. Power Generation	① Reduce the share of coal-fired power generation by shutting down coal-fired power plants ② Review the tax rate system ③ Establish the eco-friendly National Electricity Supply Plan ④ Increase the share of renewable energy
	2. Industries	⑤ Extend the scope of targets for regulating emission caps ⑥ Introduce emission charges for NOx
	3. Transportation	⑦ Reduce emissions from diesel vehicles ⑧ Increase the use of eco-friendly vehicles ⑨ Implement a Bonus–Malus System ⑩ Strengthen control over fine dust emissions from vessels
	4. Everyday Surroundings	⑪ Establish intensive control over construction sites ⑫ Distribute road-cleaning vehicles
Vulnerable Groups	5. Infrastructure and Services to Protect Vulnerable Groups	⑬ Formulate standards for indoor air quality in buildings ⑭ Strengthen monitoring networks in daycare centers ⑮ Install more indoor sports facilities in schools ⑯ Provide visits and care services for vulnerable groups
Solid Foundation for Policy Implementation	6. Solid Foundation for Scientific Management	⑰ Monitor air quality using environmental satellites ⑱ Implement the national project of PM reduction strategies

Figure 6. Structure of the *Comprehensive Plan on Fine Dust Management*. Source: [37].

4.7. Synthesis of Analysis Results

The procedural rationality of the Korean policy on ultra-fine dust has been analyzed above. Six steps of policy processes were adopted as a framework of analysis: problem identification, goal setting, searching for alternatives, consequence prediction, comparison of alternatives, and policy decision. To summarize, objective problems with regard to $PM_{2.5}$ were ascertained, and a subjective definition in public perception was verified at the *problem identification* step. The intent of the policy was a remedy, and targets were deemed desirable at the *goal setting* step. The Ministry of Environment collected policy means from experiences, theories, experts, and stakeholders at the *searching for alternatives* step. To anticipate future results of individual alternatives, research institutes utilized modeling, experiments, and intuitions at the *consequence prediction* step. Also, the government accepted effectiveness, efficiency, equity, and feasibility as criteria for assessment in the *comparison of alternatives* step. Finally, there were two major decisions made in 2013 and 2018 at the *policy decision* step. Figure 7 indicates the synthetic results of this analysis in a diagram.

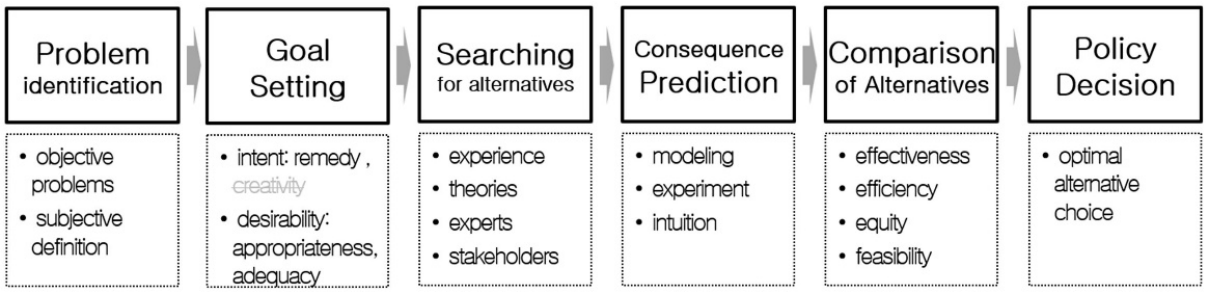


Figure 7. Results of analysis. Note: a *gray strikethrough* indicates a sub-component that was excluded and not applicable.

5. Conclusions, Implications, and Future Research Works

This study aimed to review the rationality of the ultra-fine dust policies in South Korea. The academic interest in this research was stimulated by a couple of previous studies: namely, Kim and Lee (2019) judged that the environmental programs enacted to reduce the emissions of fine particles had failed [13]; furthermore, Choi and Kim (2016) insisted that the fundamental reason for this policy failure was caused by path dependency [14]. In these two studies, the authors asserted that Korean policies with regard to fine particulate matter were improperly designed, irrationally executed, and inappropriately evaluated by the government. In contrast, this study attempted to refute their opinions by adopting procedural rationality as a framework of analysis and proved that the Korean policy scheme was significantly reasonable and rational.

Even though only one case of the Seoul Metropolitan Area was analyzed in this study, the results of the analysis could apply to other cities. Particularly, megacities in developing countries such as China, India, and Vietnam suffer from severe air pollution because of coal consumption. These similar metropolitan and capital areas need to be independent from irrational and political decision-making processes with regard to air pollution. This paper suggests that they should adopt six-step rational policy procedures like the Seoul Metropolitan Area.

In conclusion, while this study demonstrates opposite findings against two previous ones, it also has several limitations. First, rationality has subjective features inevitably. In other words, rationality is not objective, and researchers' subjective judgments cannot help but intervene in their qualitative analyses. Second, this study analyzed only procedural rationality, not substantive rationality. Nevertheless, as insisted by Simon (1976), procedural rationality is more important, and it is a central concept for policy analysis owing to the imperfections of substantive rationality [45]. For these reasons, this study just focused on procedural rationality. Lastly, follow-up studies could be expanded in other metropolitan cities in developing countries or compare the results of this analysis with other domestic cities in South Korea. In addition, research on substantive outcomes of air pollution regulations could be meaningful and helpful for policy-makers by utilizing scientific simulations and experiments.

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References

1. Apergis, N.; Ozturk, I. Testing Environmental Kuznets Curve hypothesis in Asian countries. *Ecol. Indic.* **2015**, *52*, 16–22. [CrossRef]
2. Grossman, G.M.; Krueger, A.B. Economic Growth and the Environment. *Q. J. Econ.* **1995**, *110*, 353–377. [CrossRef]

3. Jiang, M.; Kim, E.; Woo, Y. The Relationship between Economic Growth and Air Pollution—A Regional Comparison between China and South Korea. *Int. J. Environ. Res. Public Health* **2020**, *17*, 2761. [CrossRef]
4. Choi, J.; Hearne, R.; Lee, K.; Roberts, D. The relation between water pollution and economic growth using the environmental Kuznets curve: A case study in South Korea. *Water Int.* **2015**, *40*, 499–512. [CrossRef]
5. Kwag, Y.; Kim, M.-H.; Oh, J.; Shah, S.; Ye, S.; Ha, E.-H. Effect of heat waves and fine particulate matter on preterm births in Korea from 2010 to 2016. *Environ. Int.* **2020**, *147*, 106239. [CrossRef]
6. Kim, E.; Kim, B.-U.; Kim, H.C.; Kim, S. Sensitivity of fine particulate matter concentrations in South Korea to regional ammonia emissions in Northeast Asia. *Environ. Pollut.* **2021**, *273*, 116428. [CrossRef]
7. Lee, G.; Ho, C.-H.; Chang, L.-S.; Kim, J.; Kim, M.-K.; Kim, S.-J. Dominance of large-scale atmospheric circulations in long-term variations of winter PM10 concentrations over East Asia. *Atmos. Res.* **2020**, *238*, 104871. [CrossRef]
8. Trnka, D. *Policies, Regulatory Framework and Enforcement for Air Quality Management: The Case of Korea*; Environment Working Paper No. 158; OECD: Paris, France, 2020; pp. 12–22. [CrossRef]
9. MOE (Ministry of Environment). *ECOREA: Environmental Review 2015, Korea*; MOE (Ministry of Environment): Sejong, Republic of Korea, 2015.
10. Ministry of Environment (MOE). Emission Reduction Program for In-Use Diesel Vehicles. *Korea Environ. Policy Bull.* **2008**, *4*, 1–16.
11. Marval, J.; Tronville, P. Ultrafine particles: A review about their health effects, presence, generation, and measurement in indoor environments. *Build. Environ.* **2022**, *216*, 108992. [CrossRef]
12. Kim, J.Y.; Yoo, J.Y.; Park, C.J. Recent Status and Policy of Fine Dust in the Metropolitan Area of Korea. *Int. J. Environ. Sci. Dev.* **2018**, *9*, 183–186. [CrossRef]
13. Kim, H.W.; Lee, J.W. Why did Seoul's Free Public Transportation Program for Reducing Fine Particulate Matter Fail?: A Political Management Perspective. *Korean J. Local Gov. Stud.* **2019**, *22*, 99–125. [CrossRef]
14. Choi, C.; Kim, C. Path Dependency and Social Amplification of Risk in Particulate Matter Air Pollution Management and its Implications. *J. Korean Reg. Dev. Assoc.* **2016**, *28*, 89–107.
15. Cairney, P. *Understanding Public Policy: Theories and Issues*, 2nd ed.; Macmillan International Higher Education; Bloomsbury Publishing: London, UK, 2019.
16. Cohen, M.D.; March, J.G.; Olsen, J.P. A Garbage Can Model of Organizational Choice. *Adm. Sci. Q.* **1972**, *17*, 1–25. [CrossRef]
17. Kingdon, J.W. *Agendas, Alternatives, and Public Policies*; Harper Collins: New York, NY, USA, 1984.
18. Crow, D.A. Policy Entrepreneurs, Issue Experts, and Water Rights Policy Change in Colorado. *Rev. Policy Res.* **2010**, *27*, 299–315. [CrossRef]
19. Rowlands, I.H. The Development of Renewable Electricity Policy in the Province of Ontario: The Influence of Ideas and Timing. *Rev. Policy Res.* **2007**, *24*, 185–207. [CrossRef]
20. Herweg, N.; Zahariadis, N.; Zohlnhöfer, R. The Multiple Streams Framework: Foundations, Refinements, and Empirical Applications. In *Theories of the Policy Process*; Weible, C., Sabatier, P., Eds.; Routledge: Abingdon, UK, 2018. [CrossRef]
21. Birkland, T.A. "The World Changed Today": Agenda-Setting and Policy Change in the Wake of the September 11 Terrorist Attacks. *Rev. Policy Res.* **2004**, *21*, 179–200. [CrossRef]
22. O'Neill, B.; Kapoor, T.; McLaren, L. Politics, Science, and Termination: A Case Study of Water Fluoridation Policy in Calgary in 2011. *Rev. Policy Res.* **2018**, *36*, 99–120. [CrossRef]
23. Kagan, J.A. Multiple Streams in Hawaii: How the Aloha State Adopted a 100% Renewable Portfolio Standard. *Rev. Policy Res.* **2018**, *36*, 217–241. [CrossRef]
24. Webber, D.J. Earth Day and Its Precursors: Continuity and Change in the Evolution of Midtwentieth-Century U.S. Environmental Policy. *Rev. Policy Res.* **2008**, *25*, 313–332. [CrossRef]
25. Howlett, M.; McConnell, A.; Perl, A. Streams and stages: Reconciling Kingdon and policy process theory. *Eur. J. Political Res.* **2014**, *54*, 419–434. [CrossRef]
26. Rawat, P.; Morris, J.C. Kingdon's "Streams" Model at Thirty: Still Relevant in the 21st Century? *Politics Policy* **2016**, *44*, 608–638. [CrossRef]
27. Huber-Stearns, H.R.; Schultz, C.; Cheng, A.S. A Multiple Streams Analysis of Institutional Innovation in Forest Watershed Governance. *Rev. Policy Res.* **2019**, *36*, 781–804. [CrossRef]
28. Mele, A.R.; Rawling, P. *The Oxford Handbook of Rationality*; Oxford University Press: Oxford, UK, 2018. [CrossRef]
29. Barros, G.; Herbert, A. Simon and the concept of rationality: Boundaries and procedures. *Braz. J. Political Econ.* **2010**, *30*, 455–472. [CrossRef]
30. Simon, H. *Administrative Behavior: A Study of Decision-Making Processes in Administrative Organization*; Free Press: New York, NY, USA, 1947.
31. Jin, S.-H.; Oh, S.-M. An Analysis on Rationality in Policy Making Process: Focusing on the Case of Seoul Energy Corporation. *Korean J. Local Gov. Stud.* **2020**, *24*, 69–93. [CrossRef]
32. IQAir. *2019 World Air Quality Report: Region & City PM2.5 Ranking*; IQAir: Goldach, Switzerland, 2020.
33. WHO. *WHO Air Quality Guidelines for Particulate Matter, Ozone, Nitrogen Dioxide and Sulfur Dioxide*; WHO: Genewa, Switzerland, 2005.
34. IARC. *Air Pollution and Cancer*; IARC Scientific Publications: Lyon, France, 2013; p. 161.

35. Park, M. An Analysis of Social Data characteristics about ultra-fine dust and future policy demand. *Mag. Korean Soc. Hazard Mitig.* **2017**, *17*, 22–31.
36. Kim, Y.J.; Kim, K.W.; Kim, S.D.; Lee, B.K.; Han, J.S. Fine particulate matter characteristics and its impact on visibility impairment at two urban sites in Korea: Seoul and Incheon. *Atmos. Environ.* **2006**, *40*, 593–605. [CrossRef]
37. Ministry of Environment (MOE). Comprehensive Plan on Fine Dust Management. *Korea Environ. Policy Bull.* **2018**, *15*, 1–32.
38. UNEP. *Actions on Air Quality: Policies & Programmes for Improving Air Quality around the World*; UNEP: Nairobi, Kenya, 2016.
39. Woo, J.-H. Review of PM-related Air Quality Improvement Policies of United States for PM-related Air Quality Improvement of Metropolitan Region in Korea. *J. Korean Soc. Atmos. Environ.* **2009**, *25*, 579–593. [CrossRef]
40. Han, H.; Jung, C.H.; Kum, H.S.; Kim, Y.P. The Revisit on the PM10 Reduction Policy in Korea: Focusing on Policy Target, Tools and Effect of 1st Air Quality Management Plan in Seoul Metropolitan Area. *J. Environ. Policy Adm.* **2017**, *25*, 49–79. [CrossRef]
41. Gong, S. *A Study on the Health Impact and Management Policy of PM2.5 in Korea (I)*; Korea Environment Institute: Sejong, Republic of Korea, 2012.
42. Gong, S. *A Study on the Health Impact and Management Policy of PM2.5 in Korea (II)*; Korea Environment Institute: Sejong, Republic of Korea, 2013.
43. Jung, T. Air Quality and Regional Co-operation in South Korea. *Global Asia* **2019**, *14*, 28–33.
44. Cha, J.; Jung, W.; Chae, S.; Ko, A.; Ro, Y.; Chang, K.; Seo, S.; Ha, J.; Park, D.; Hwang, H.; et al. Analysis of Results and Techniques about Precipitation Enhancement by Aircraft Seeding in Korea. *Atmosphere* **2019**, *29*, 481–499. [CrossRef]
45. Simon, H. From substantive to procedural rationality. In *Method and Appraisal in Economics*; Spiro, L., Ed.; Cambridge University Press: Cambridge, UK, 1976; pp. 129–148. [CrossRef]

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Review

An Overview of the Role of Forests in Climate Change Mitigation

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Abstract: Nowadays, climate change is recognized as one of the biggest problems the world is facing, posing a potential threat to the environment and almost all aspects of human life. Since the United Nations Framework Convention on Climate Change in 1992, many efforts have been made to mitigate climate change, with no considerable results. According to climate change projections, temperatures will continue to rise, and extreme weather events will become more frequent, prolonged, and intense. Reflecting these concerns, the 2015 Paris Agreement was adopted as the cornerstone for reducing the impact of climate change, aiming to limit global warming below 2 °C and even keep the temperature rise below 1.5 °C. To achieve this international goal, focused mitigation actions will be required. Climate change has a strong impact on forests, enhancing their growth but also posing risks to them. Conversely, forests can mitigate climate change, as they have a considerable impact on global surface temperatures through their influence on the land–atmosphere energy exchange and the absorption of vast amounts of CO_2 through photosynthesis. Consequently, afforestation and reforestation have become integral components of climate change mitigation strategies worldwide. This review aims to summarize the cutting-edge knowledge on the role of forests in climate change mitigation, emphasizing their carbon absorption and storage capacity. Overall, the impact of afforestation/reforestation on climate change mitigation hinges on strategic planning, implementation, and local forest conditions. Integrating afforestation and reforestation with other carbon removal technologies could enhance long-term effectiveness in carbon storage. Ultimately, effective climate change mitigation entails both restoring and establishing forests, alongside reducing greenhouse gas emissions.

Keywords: forest; reforestation; afforestation; climate change; sustainability

1. Introduction

Climate is in constant interaction with natural ecosystems and humans, affecting all aspects of life, including work, nutrition, health, economy, and general well being. Since the onset of the industrial revolution, excessive use of fossil fuels and changes in land use have resulted in disrupted weather patterns, the impacts of which often surpass the resilience limits of ecosystems. Climate change has been linked to numerous adverse outcomes, including food insecurity, reduced availability and quality of potable water, biodiversity loss, the transmission of infectious diseases, destruction of infrastructure, and public health stress [1]. Consequently, it is regarded as one of the most critical challenges the modern world faces.

Climate change was recognized as a global political issue approximately half a century ago, and since then, mitigation efforts have been steadily increasing. Milestones in this endeavor include the adoption of the United Nations Framework Convention on Climate Change (UNFCCC) during the 1992 United Nations Conference on Environment and Development (UNCED), also known as the Earth Summit, the signing of the Kyoto Protocol in 1997, and the establishment of the Paris Agreement in 2015. The Paris Agreement set

ambitious targets, aiming to hold the global average temperature rise to well below 2 °C compared to pre-industrial levels, with aspirations to limit it to 1.5 °C. In line with these efforts, the European Union, through the Green Deal, has taken a leading role in combating climate change, intending to achieve climate neutrality by 2050.

In recent years, as efforts to develop measures and strategies for mitigating and adapting to climate change have intensified, there has been an increasing focus among policymakers and the scientific community on nature-based solutions. These solutions comprise a broad framework of integrated ecosystem-based approaches aimed at addressing societal and environmental challenges while considering environmental, social, and economic aspects and interconnections. Nature-based solutions involve the preservation, restoration, and sustainable management of natural ecosystems, including forests, wetlands, grasslands, and coastal areas [2]. Considering the capacity of forests to sequester atmospheric carbon dioxide (CO_2), reforestation actions, integral to the framework of nature-based solutions, could be very effective in the fight against climate change.

In addition to their impact on climate, trees and forests offer multiple additional benefits, including biodiversity conservation, soil and water retention, air and water pollution mitigation, and economic growth, e.g., refs. [3–7]. It is also worth noting the significant role of urban forests in mitigating the urban heat island effect [8,9], wherein temperatures in urban areas are notably higher compared to surrounding suburban and rural areas [10]. Finally, there is evidence that forests have a positive effect on people's concentration, anxiety and depression management, and overall emotional and mental health [11,12]. In conclusion, forests play a multifaceted role, providing invaluable benefits to both the environment and humans.

This review aims to elucidate the role of forests in climate change mitigation by thoroughly examining the diverse dimensions of the underlying interactions. It delves into the impact of forests on climate, focusing on their carbon removal and storage capabilities, while also assessing the effect of biophysical processes, such as evapotranspiration and surface albedo. The review explores both natural and anthropogenic disturbances that affect forest ecosystems. Furthermore, it evaluates the efficacy of afforestation and reforestation in carbon sequestration while also examining their implications for food security. In addition, it investigates the overall impact of such actions as well as the nuanced factors affecting their effectiveness. Overall, this review contributes to advancing the understanding of the nexus between forests and climate, highlighting the importance of afforestation and reforestation in global efforts to mitigate climate change.

2. The Role of Forests in Shaping Climate

Forests are complex ecosystems teeming with diverse flora and fauna. Although there is no single definition, the Food Agriculture Organization (FAO) of the United Nations (UN) describes a forest as a land area of more than 0.5 ha with trees over 5 m tall, or with trees capable of reaching this height, and a canopy cover of more than 10% [13].

The impact of forests on climate is mainly linked to the biochemical processes of trees (Figure 1), such as photosynthesis, which affect CO_2 levels in the atmosphere, playing an important role in the carbon cycle [14,15]. Trees, along with other plant organisms within forests, sequester CO_2 from the atmosphere during the process of photosynthesis. A proportion of this carbon is stored in the stems, branches, and roots of trees and plants, in dead organic matter, and within soil. The rest is released into the atmosphere as CO_2, mainly through the respiration of trees and plants, as well as through the decomposition of dead organic matter [15]. In addition to the respiration process, CO_2 emissions may be caused by forestry activities related to their management, as well as from deforestation and/or degradation due to natural disturbances (e.g., fires, droughts, etc.) and anthropogenic interventions (e.g., deforestation for land use change and/or exploitation of timber products) [16,17].

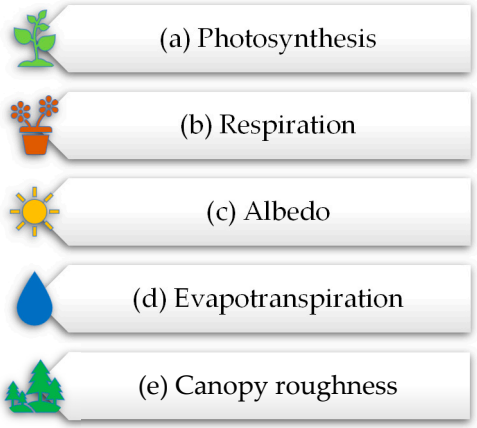


Figure 1. The biochemical (a and b) and biophysical (c, d, and e) mechanisms of trees that affect the climate.

In forest ecosystems, the equilibrium between carbon stocks and emissions has an important impact on climate. A forest is deemed a net carbon sink when it absorbs and stores more carbon than it emits over a defined period. Otherwise, it is considered a net carbon source [18]. Although carbon stocks in different forest ecosystems around the world exhibit notable variations related to various factors, such as biodiversity [19], tree characteristics (e.g., species, age) [20,21], climatic conditions [22], and forest management [23,24], on a global scale, forest ecosystems act as net carbon sinks, contributing to mitigating the increase in global average temperature [25–28]. In 2020, the global forest carbon stock was approximately 662 Gt, with 44% attributed to tree mass (root system, wood, bark, and leaves), 45% to soil organic matter, and the remainder to deadwood and litter [29].

However, some researchers have reported that forests acted as weak net carbon sources at the global level during specific time periods between 1990 and 2020. This was probably related to extensive deforestation and increased forest degradation, mainly due to anthropogenic interventions [30,31]. Additionally, high temperatures and elevated Vapor Pressure Deficits (VPDs) have been observed to affect photosynthesis and respiration in trees, disturbing their balance under certain conditions. This can potentially undermine the role of forests as carbon sinks [32–35]. Nevertheless, it is important to acknowledge that the modeling and quantification of carbon fluxes in forest ecosystems are complex processes. They are influenced by numerous factors, and their results involve a high degree of uncertainty, as they depend on the data used, the methodology followed, and the assumptions adopted [15,30,31,36,37].

Apart from their impact on the carbon cycle, forests influence the climate, primarily at local and regional levels, through biophysical mechanisms, including reflectivity (albedo), evapotranspiration, and canopy roughness [14] (Figure 1). Due to their dark color, forests possess lower albedo than that of soil, snow, grazing lands, cultivated lands, and low vegetation [14]. Consequently, forests absorb a greater percentage of incident solar radiation, enhancing climate warming at local and/or regional levels [38,39]. Additionally, a portion of the incident solar radiation is absorbed during evapotranspiration. This process involves the evaporation of water from the soil surface and plants, as well as transpiration, where water is transferred through the root system from the soil to the leaves and emitted as water vapor. Through evapotranspiration, sensible heat, associated with air temperature rise, is converted into latent heat to change the phase of water from liquid to gas (water vapor) [39,40]. Furthermore, the relatively high roughness of the forest canopy favors vertical mixing of the air and latent heat transfer (via water vapor) to higher altitudes, eventually cooling the soil locally [40]. Under certain conditions, the cooling effect on soil is augmented by the condensation of water vapor, leading to cloud formation and higher albedo. However, as water vapor is a greenhouse gas, it can counteract the cooling effect of clouds, affecting the overall surface energy balance [40].

On the whole, it is evident that the influence of biophysical mechanisms on climate is complex and varies greatly, depending on regional characteristics. As biophysical mechanisms can either enhance or counteract heat storage, they contribute to climate warming or cooling, respectively, e.g., refs. [40–43]. On the other hand, the interactions among biophysical mechanisms and their overall impact on climate exhibit high spatial variability, posing challenges in accurate quantification [40,44]. Generally, due to the low albedo of forests, the intensity of warming increases with latitude, while the intensity of cooling decreases due to evapotranspiration. For example, in tropical regions, the increase in soil temperature resulting from the low albedo of forests is counteracted by the intense cooling caused by high evapotranspiration rates, leading to climate cooling on an annual basis [18,39,45]. On the other hand, in the boreal forest, warming due to low albedo greatly exceeds the cooling caused by evapotranspiration, especially during winter months when snow cover is typically high [14,39,46]. For temperate forests, the impact of their biophysical mechanisms on climate remains uncertain [14,39,46,47]. Irrespective of the climatic zone, though, the biophysical mechanisms of forests play an important role in reducing diurnal and annual temperature fluctuations, as well as moderating extreme temperatures during the summer period, particularly during the day [39,46].

Overall, forests are vital for climate stability and for mitigating climate change, but it should be noted that their ability to continue playing this role is increasingly at risk due to a combination of natural and human-induced pressures.

3. Natural and Anthropogenic Disturbances of Forests

Anthropogenic activities, including deforestation, logging, and harvesting of wood for fuel, combined with natural disturbances, such as storms, fires, droughts, diseases (e.g., from fungi, pests, or insects), and other extreme weather events, put continuous pressure on forest ecosystems [48–52]. As natural disturbances depend on local climate conditions, due to climate change, an increase in their frequency and severity is expected [53]. The combined effect of these disturbances seriously threatens forests' sustainability, impairing their capacity to store carbon. For example, Yang et al. (2018) found that during the period from 2005 to 2008, the Amazonian forests experienced an average carbon loss rate of 0.3 PgC yr^{-1}, primarily attributed to the prolonged 2005 drought [54].

Despite continuous global efforts in recent decades, deforestation remains a major environmental problem [29–31,36]. From 1990 to 2020, approximately 420 million ha of forests were lost globally, with the annual rate of deforestation decreasing by 5.6 million ha from 1990–2000 to 2015–2020 [29]. Notably, over the period of 2012–2021, global CO_2 emissions from deforestation accounted for about 17% of total annual CO_2 emissions, amounting to about 6.6 Gt CO_2 yr^{-1} (≈1.8 GtC), with the tropics making the largest contribution [32]. Tropical deforestation alone has been estimated to be responsible for 2.3–6.2 Gt CO_2 yr^{-1} [23,55,56]. Nevertheless, caution is needed when comparing CO_2 emissions, as these values depend on the method and assumptions adopted for their calculation, as well as the timeframe under consideration [56].

Furthermore, although wildfires, as natural occurrences in forest ecosystems, play a vital role in regulating ecological processes and supporting crucial ecosystem services while promoting biodiversity preservation and enhancement [57,58], they also rank among the most common disturbances affecting forests globally [59,60]. Despite a decrease in global burnt areas over the last two decades, there has been a slight increase in forest fire emissions [61]. According to Zhao et al., (2021b), between 1986 and 2016, CO_2 emissions from wildfires in the Alaskan and Canadian boreal forests were estimated at 57.1 TgC per year [62]. Similarly, the average annual emissions from wildfires in Siberia, between 2002 and 2020, were estimated at 80 ± 20 Tg C/year. However, there were notable sporadic peaks during this period, with 2020 recording the highest emissions at approximately 350 Tg C/year [63]. In addition, the emissions from the Southeast Australian wildfires during the 2019–2020 summer season were estimated to be 715 Tg CO_2 (517–867 Tg CO_2) [64]. From 2001 to 2018, fires affected approximately 7.2 billion ha globally, 29% of which were

in tree-covered areas (not necessarily classified as forests) located in the tropics [29]. Additionally, according to Van Lierop et al., (2015), from 2003 to 2012, the annual burned forest area globally averaged 67 million ha, with more than 53 million ha located in the tropics [59]. In 2023, wildfire activity was exceptionally high in many regions worldwide. Canada was affected the most, experiencing intense and persistent fires from May to October. As a result, almost 7.8 million ha of forest land were burned, accounting for over 25% of the total global tree cover loss, and nearly 3 billion tons of CO_2 were emitted [65]. Similarly, Greece faced severe wildfires during the summer of 2023, primarily on the island of Rhodes and in the northeastern part of the country, with the wildfire in the latter being the largest recorded in the history of the European Union. Overall, these wildfires in Greece emitted approximately 2 MtC (Copernicus: https://atmosphere.copernicus.eu/ accessed on 6 June 2024).

Additionally, it is important to highlight that due to climate change, an increase in the frequency of wildfires caused by high temperatures and droughts is predicted, with the Mediterranean region being particularly vulnerable [51,66–69]. In response, efforts by governments and organizations worldwide to enhance protection measures against the threat of forest fires have been burgeoning in recent years (European Commission: https://drmkc.jrc.ec.europa.eu/ accessed on 6 June 2024; European Forest Institute: https://efi.int/ accessed on 6 June 2024; Government of Canada: https://www.canada.ca/ accessed on 6 June 2024). However, strict fire control can impact the structure and functions of forest ecosystems in several ways, including shifts in species composition and biodiversity reduction [70,71]. There is evidence suggesting that aggressive fire suppression policies favor the accumulation of flammable vegetation, increasing the risk of large and intense fires, especially under the impact of ongoing climate warming. Therefore, it is recommended to adopt a holistic forest fire management approach that considers the aforementioned parameters and integrates proactive measures to complement fire suppression efforts [72,73]. In addition to the disturbances mentioned earlier, each year approximately 6 million ha of forest areas are affected by extreme weather events, 4.8 million ha by diseases, and 29 million ha by insects [29]. Considering the challenges associated with accurately recording forest areas affected by these disturbances and the inconsistency in doing so, these rates may potentially be higher in reality [51].

Given the challenges posed by natural and anthropogenic disturbances, the need for proactive measures becomes evident. Transitioning from understanding these threats to addressing them, the focus shifts to exploring the pivotal role of afforestation and reforestation in restoring and enhancing forest ecosystems.

4. Afforestation and Reforestation

The imperative role of forests in removing CO_2 from the atmosphere underscores the importance of their restoration, expansion, and proper management in achieving the Paris Agreement targets and mitigating climate change [27,30,41,74]. According to the international literature, the restoration of degraded forest ecosystems could substantially offset CO_2 emissions resulting from forest degradation and deforestation caused by natural and/or anthropogenic disturbances [15,18,36,49]. Given the environmental and socioeconomic impacts of forest degradation, the scientific community has a particular interest in issues related to sustainable forest development and restoration, e.g., refs. [75–78]. Tree planting initiatives to restore and expand forests through afforestation and reforestation campaigns are recognized as an efficient and cost-effective solution, e.g., refs. [41,79–81], and are highly valued by both stakeholders and the general population. It is of note that afforestation refers to the process of planting trees to create new forests in areas devoid of forest cover for at least the past 50 years, while reforestation refers to the restoration of forests that have been impacted by natural or anthropogenic disasters [82]. Nevertheless, the term "reforestation" is often used interchangeably for both activities.

According to FAO [29], in 2020, the area of planted forests created through afforestation and reforestation encompassed approximately 294 million ha, accounting for 7% of

the world's total forests. Between 1990 and 2020, the area of planted forests increased by 123 million ha globally, although the average annual growth rate decreased from 5.13 million ha in 2000–2010 to 4.06 million ha 2010–2020. Notably, in Asia, 22% of forests are attributed to tree planting operations, while the equivalent percentage in Africa and South America is only 2%. The percentage of planted forests is slightly higher in North and Central America, reaching 6% of the total forest area in each region. Europe shows higher rates, with human intervention contributing to 30% of forests, excluding the European part of Russia. However, when including Russia's predominantly natural forests, the percentage drops to 7% (Figure 2).

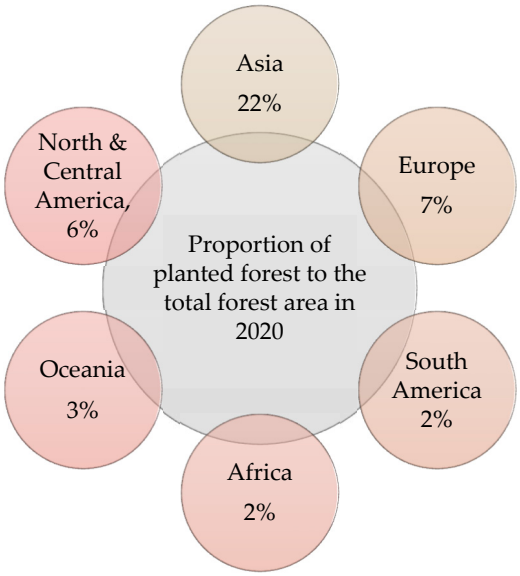


Figure 2. The percentage of forest attributed to tree planting operations in various parts of the world in 2020.

As national agreements on climate change mitigation highlight the crucial role of CO_2 sequestration, large-scale afforestation and reforestation actions are pivotal in addressing climate change, despite variations in specific land requirements and their effectiveness. Numerous researchers have focused on assessing the effectiveness of afforestation/reforestation practices to tackle climate change by quantifying the CO_2 sequestration capacity of forests, e.g., refs. [41,83,84]. For instance, acknowledging the value of urban forests for local communities [4,7,10,11] and spurred by the increasing prevalence of afforestation programs in various urban areas worldwide [85–87], Teo et al. (2021) evaluated the potential contribution of urban forests to climate change mitigation [88]. Specifically, after identifying areas suitable for planting new forests within 7595 urban centers worldwide, they calculated the potential carbon sequestration capacity of the aboveground woody biomass (i.e., carbon stored in trees, branches, leaves, and other aboveground vegetation). According to their findings, approximately 17.6% of the total urban areas studied were potentially suitable for afforestation. This rate corresponds to approximately 10.9 Mha and has the potential to sequester 82.4 $\pm$ 25.7 Mt CO_2 eq annually. Overall, they concluded that afforestation of available urban areas could significantly contribute to CO_2 emissions mitigation, offsetting more than 1/4 of local emissions. However, when comparing the carbon sequestration rates of urban and non-urban forests, they observed that non-urban forests tended to prevail.

Furthermore, a study by Bastin et al. (2019) has sparked considerable interest [75]. They explored the potential changes in tree cover and the carbon storage capacity in forest ecosystems globally, considering the impact of climatic, soil, and topographic parameters. Overall, they concluded that forest ecosystem restoration through afforestation, reforestation, and natural forest regeneration is one of the most effective methods for mitigating

climate change. According to their estimates, excluding existing trees, cultivable land, and urban areas, forests could expand by 0.9 billion ha globally, potentially storing up to 205 GtC. This amount corresponds to approximately 70% of total carbon concentrations in the atmosphere resulting from anthropogenic activities. However, a part of the scientific community [79,89–91] has expressed objections regarding the validity of the aforementioned results. Critics have pointed out simplifications and inaccuracies in calculations, including the omission of existing vegetation and soil organic carbon stocks, as well as the biophysical impact of forests on climate. In response, Taylor and Marconi (2020) [91] estimated that by increasing forests by 0.9 billion ha, global carbon stocks would range between 71.7 and 75.7 GtC, which is approximately 40% less than the estimations provided by Bastin et al. (2019) [75].

Nevertheless, large-scale afforestation/reforestation actions, such as those presented above, require extensive land areas, a portion of which may already serve (or could potentially serve) other uses, such as food production [16,92]. Therefore, extensive tree planting in areas devoid of previous land cover could pose risks to local and global food security. As pointed out by Kreidenweis et al. (2016), increasing forest area by 60% globally would result in the sequestration of approximately 860 Gt CO_2 by the end of the century, causing, however, food prices to more than quadruple [93]. Similar conclusions have been drawn for other land-based climate change mitigation measures, such as bioenergy production [94–97]. It is noteworthy that one-third of the countries participating in the Bonne Challenge face difficulties in meeting their targets without impacting food production. These difficulties stem from their commitment to restore degraded forests and plant trees covering more than 10% of their total land area, as outlined in the Bonne Challenge [98].

Similarly, Doelman et al. (2020) demonstrated that in order to keep the average global temperature increase below 2 °C by the end of the century (compared to pre-industrial times), a total of 410 Gt of CO_2 must be sequestered [80]. They also estimated that to achieve this target, it is necessary to expand forests by approximately 1.1 billion ha. According to their estimates, this would result in reduced food availability and increased food prices, which would put an additional 441 million people worldwide at risk of undernourishment by 2100 compared to 2010 levels. In addition, considering the findings of Doelman et al. (2020) [80] and other similar studies [95–97], it can be concluded that developing regions already facing severe nutrition challenges, particularly Africa and South Asia, are expected to experience the greatest impact. Despite the high uncertainty of these results, it is recommended that climate change mitigation strategies involving large-scale land planting take into account potential risks to food security and adopt suitable mitigation practices [80]. For instance, agroforestry, which integrates the cultivation of trees and shrubs with crops and/or livestock on the same land, constitutes a promising land management practice that effectively addresses the conflict between forest conservation and food production. It supports all four aspects of the food and nutrition security framework (availability, access, utilization, and stability) while delivering positive economic impacts for farmers and offering environmental advantages, such as enhanced biodiversity and water quality, improved soil health, and carbon sequestration. Overall, agroforestry presents a balanced and sustainable solution, favoring both climate change mitigation and adaptation [99–101].

5. Parameters Affecting the Effectiveness of Forests and Afforestation/Reforestation in Climate Change Mitigation

5.1. Factors Related to Forest Characteristics

The ability of forests to sequester and store carbon, and, consequently, the effectiveness of afforestation/reforestation programs in climate change mitigation, exhibit spatial and temporal variations, depending on various factors. These factors include, among others, local climatic conditions, density and diversity of forest vegetation, tree age and species, and soil characteristics, e.g., refs. [15–20,102–106].

Li et al., (2023), who studied a forest with approximately 2000 fir trees in Southern China, gradually planted as part of reforestation efforts in the region, found that the

total carbon stocks of the ecosystem increased with increasing tree age [21]. Consistent with findings from previous studies, e.g., refs. [15,24,107], they observed that the CO_2 sequestration rate gradually increased until the middle age of trees, where it peaked and then decelerated considerably, highlighting the role of tree aging in carbon sequestration rates. Bernal et al. (2018), taking into account the impact of various factors, such as climatic conditions, latitude, tree age, and species, assessed the carbon sequestration rate and storage for a set of different forest landscape restoration actions, including natural forest regeneration and afforestation/reforestation [108]. According to their findings, the growth rate of forest biomass, and thus the carbon removal rate from the atmosphere, was higher during the first 20 years of forest restoration. However, in some cases, such as in regions with high annual precipitation in North America, Asia, and Oceania, the growth rate of forest biomass was found to be as high or higher over the period between 20 and 60 years old [108].

Bernal et al. (2018) also observed that the CO_2 removal rates from trees, regardless of their species, exhibited an increasing trend from colder to warmer climates [108]. Similarly, Chiquier et al. (2022) estimated that the maximum CO_2 sequestration potential per ha of boreal forests in the United Kingdom was approximately six times smaller than that of the tropical forests in Brazil [17]. Additionally, they observed that high levels of rainfall enhanced the CO_2 sequestration potential of tropical forests [17]. Similarly, Balima et al. (2021) found that high mean annual precipitation enhances carbon storage in aboveground tree biomass in West Africa, but they observed that increased mean annual temperature has a negative impact [109]. According to Wang and Huang (2020), tropical climate regions presented the highest rate of carbon sequestration from aboveground tree biomass, while the maximum carbon sequestration rate from forest soils was observed for warm temperate climate regions [81]. They also found that latitude, mean annual rainfall, and the number of frost-free days were among the factors determining the carbon sequestration rate from soil, highlighting that their contribution varies, depending on the climate of the region under study [81].

Interestingly, Wen and He (2016) found that temperature and rainfall positively affected carbon storage in the vegetation of forests in eastern China but had a negative impact on soil carbon storage [110]. Overall, the growth rate of trees is related to local climatic conditions, thereby affecting their ability to sequester and store carbon in their biomass [104,106]. This is because the processes of photosynthesis and respiration in trees depend on climatic parameters, such as temperature, precipitation levels, and cloud cover, with the magnitude of their effects varying based on the climatic characteristics of each region [111,112]. For instance, there is evidence that under the influence of hot and dry conditions, respiration can exceed photosynthesis, counteracting the benefits of forests as carbon sinks [32–34]. However, the impact of these climatic parameters on soil carbon stocks in forest ecosystems is complex, mainly depending on the balance between organic matter inputs into the soil and decomposition processes [110].

Other factors that may affect total carbon stocks in forests are the density and species of trees. Consistent with findings from previous studies [77,106], Osei et al. (2022), focusing on European forest ecosystems, observed that stand density, expressed as basal area per hectare, strongly affects the carbon stored in tree woody biomass, whereas its impact on soil carbon stock is negligible [113]. However, contradictory conclusions have emerged from studies focusing on coniferous forests of the Pinaceae family [114,115]. Furthermore, in the study by Osei et al. (2022), it was found that broadleaved species, such as beech and oak, store more carbon in their aboveground woody biomass (stem and branches) than in the soil (forest floor and down to a depth of to 40 cm depth), whereas, in the case of pines, carbon is evenly distributed between these two pools [113]. They also observed that, in all species studied, the carbon stored in their coarse root system is lower compared to the carbon stored in their aboveground biomass. In the same vein, Bernal et al. (2018) observed variations in the carbon sequestration rate of different species in the same climatic zone [108].

In line with the findings of Bernal et al. (2018) [108], numerous studies confirmed that soil carbon stocks vary, depending on tree species [103,116–118]. Such observations presumably stem from the fact that the species of a tree affects both the quantity and the quality of carbon deposition, thereby determining the decomposition rate and the fraction of organic matter that remains in the soil or is released as CO_2 [119–121]. Nevertheless, while species composition, as well as stand density, undoubtably influence total carbon stocks and the distribution between aboveground woody biomass and soil, evidence suggests that they cannot fully account for the variability in soil carbon storage [113]. This indicates that soil carbon stocks in forests may also be affected by other factors [103], such as climatic conditions, soil characteristics (e.g., texture, moisture, chemical composition), and the topography of the area [122].

In addition to the factors previously discussed, there is evidence that increased tree species diversity enhances soil organic carbon (SOC) storage in forests [19,77,123]. For instance, Osei et al. (2021), who studied several mixed stands comprising two different species as well as their corresponding pure stands across seven European countries, discovered that oak–beech pairs promoted carbon storage at soil depths of 0–10 cm, while pine–oak pairs promoted it at depths of 10–40 cm [124]. However, when assessing the total carbon stocks from the soil surface to a depth of 40 cm, they found no significant variation associated with the coexistence of the species under study. Furthermore, while some studies suggest that monocultures exhibit higher CO_2 sequestration rates, especially when appropriate management schemes are implemented [125–127], high tree diversity has also been positively associated with increased aboveground carbon stocks of forests [128–131]. Nevertheless, in agreement with previous studies [77,132], Osei et al. (2021) concluded that although tree diversity may affect soil carbon stocks of forests, its impact is smaller compared to the effect of tree species identity [124].

5.2. Factors Related to the Implementation of Afforestation/Reforestation Actions

Based on the previous discussion, it is evident that forests are complex ecosystems with many, and often interdependent, factors affecting their capacity to sequester CO_2 from the atmosphere. In addition to these factors, various parameters occurring during the implementation of afforestation/reforestation actions, such as soil carbon losses resulting from ground preparation before tree planting, may play an important role. Specifically, the type and intensity of the afforestation/reforestation practices used are determined by soil characteristics (e.g., its mineral content) and may lead to high soil carbon emissions for several years [16]. Furthermore, climatic conditions, soil composition, and moisture levels can affect the decomposition rate of deposits and may contribute to the accelerated mineralization of organic soil carbon, increasing greenhouse gas emissions [133]. All these factors, along with the low CO_2 sequestration rate and deposition rate typical of young trees, are likely to result in a substantial reduction in soil carbon stocks and may impede the ability of new forests to function as net carbon sinks during the first ten years after their establishment [17,133].

Additionally, the amount of carbon stored in the soils of afforested/reforested areas depends, to a large extent, on the previous land use [117,122,134]. For example, there is evidence that tree planting in croplands increases soil carbon stocks, whereas in grasslands and peatlands, soil carbon stocks remain stable or decrease [77]. Similar conclusions were reached by Friggens et al., (2020) while studying soil carbon stocks 12 and 39 years after planting pines and oaks in peatlands in Scotland [135]. In the same vein, Hüblová and Frouz (2021) observed that soil carbon stocks are higher after tree planting in areas previously characterized as forests or agricultural lands compared to areas that had undergone mining activities [136]. Specifically, they found that in forests, agricultural areas, and soils with relatively low pH and/or high sand content, planting coniferous trees contributed to higher organic carbon stocks compared to planting broadleaf trees. Conversely, the opposite trend was observed in areas previously affected by mining activities [136].

5.3. Climate Change

Climate change has a complex effect on forests' growth and health. Higher levels of CO_2 and higher temperatures related to climate change can prolong the growing season and enhance forest productivity, potentially resulting in higher sequestration rates (EPA: www.epa.gov accessed on 6 June 2024). However, this positive impact presents regional variability, varies between tree species, and depends on the level of projected temperature increase (EPA: www.epa.gov accessed on 6 June 2024) [137,138]. Furthermore, the more frequent and intense occurrence of forest disturbances due to climate change, such as insect outbreaks, wildfires, droughts, and storms, can counteract its positive effect on forest growth and productivity (EPA: www.epa.gov accessed on 6 June 2024). Excluding the impact of forest disturbances, climate change is expected to favor carbon sequestration in forests located in the mid to high latitudes of the Northern Hemisphere, particularly in Northeast and Central Asia, Northern Europe, and Northwestern America. On the other hand, forests in South America and Central Africa will probably be adversely affected [28].

In addition, various studies suggest that under the influence of a rapidly changing climate, local habitat suitability for the growth and thriving of species will change, resulting in some species benefiting and others facing challenges [139,140]. It is, therefore, crucial to conduct a thorough long-term assessment of a region's capacity to support each species to be planted, as this has a strong impact on its growth and, overall, the new forest's ability to remove CO_2 from the atmosphere. In general, for forests and afforestation/reforestation actions to effectively contribute to a sustainable and resilient future, a balanced approach is necessary. This approach should combine long-term planning to guide future decision making, as well as the implementation of strategies that yield immediate impacts on climate change mitigation and adaptation to its effects. Reconciling the need for comprehensive long-term assessments with the urgent need to address climate change in the near future presents a critical challenge.

An illustrative example is the study conducted by Baggio-Compagnucci et al., (2022) on the assessment of afforestation as a strategy for CO_2 mitigation in Scotland, where they observed that climate variations have different impacts on carbon stocks in tree biomass, depending on their species [16]. Additionally, they found that by 2050, the lowland areas of Scotland will become more conducive for species that typically thrive in temperate climates with mild temperatures (e.g., Pedunculate Oak, Ash, Wych Elm), while these areas will be less conducive for species that thrive in cold climates and boreal forests (e.g., Betula sp.) [16].

On the other hand, climate change is expected to result in spatially heterogeneous increases in the intensity and frequency of disturbances that afflict forests (e.g., heatwaves, fires, droughts, biotic agents, such as insects, etc.), adversely affecting their CO_2 sequestration capacity and decreasing their carbon stocks [51]. In addition, the impact of climate change on forests, combined with other factors, such as air pollution and invasive species, can exceed their limits of resilience, resulting in their conversion into grasslands or savannahs [141]. Consequently, in regions that are heavily affected by such stressors and where vulnerability is projected to increase due to climate change, the benefits expected from afforestation/reforestation need to be carefully evaluated, and appropriate management measures need to be implemented in order to minimize potential adverse impacts [141].

5.4. Biophysical Mechanisms of Forests

Planting trees in previously non-forested areas usually leads to a decrease in surface albedo. This, in conjunction with other biophysical and biochemical mechanisms of forests, can affect local and regional climate, depending on the latitude [14,40,44]. For instance, in tropical regions, tree planting constitutes an extremely effective way to mitigate temperature rise. In these regions, the prevailing climatic conditions also play an important role, favoring the rapid growth of trees and thus the high CO_2 sequestration rate [40,53,84]. On the other hand, the effectiveness of afforestation in the boreal forest zone is disputed, as the

change in surface albedo caused by tree planting is likely to offset the temperature decrease that could be achieved by CO_2 sequestration, causing local temperature increase [40,42].

Of particular interest is a recent study by Breil et al. (2023), which evaluated the climatic impact of covering the entire European continent with trees, assuming greenhouse gas concentrations at pre-industrial levels [43]. According to their findings, the implementation of this hypothetical afforestation would cause climate warming in Europe. This highlights the strong influence of biophysical processes, which exceed that of biochemical processes in the region under study. Therefore, it is crucial to consider the combined effect of biophysical and biochemical processes when assessing the impact of afforestation on local or regional climate [17,43]. However, the overall contribution of forests to carbon sequestration and their role as important carbon sinks highlight the importance of considering the cost/benefit needs on a global scale. In any case, even when forests are associated with local/regional climate warming, they contribute substantially to air and water quality, biodiversity, human well being and leisure, the provision of forest products, etc. [42].

6. Exploring the Overall Impact of Afforestation and Reforestation

As demonstrated in the previous section, to maximize the benefits of afforestation/reforestation in climate change mitigation, it is crucial to plant the right tree in the right place [124,136]. However, to ensure that afforestation/reforestation is a successful nature-based solution (NBS), its impact on other sectors, such as biodiversity conservation/enhancement and economic enhancement, needs to be also assessed. For example, afforestation of areas, such as savannahs, grasslands, peatlands, and wetlands, contributes to carbon removal from the atmosphere, but it may also lead to devastating impacts on local biodiversity [2]. Additionally, it could jeopardize food security [80] and local water resources, particularly in developing countries and dry regions [142,143]. Therefore, to ensure sustainability and resilience, all potential risks involved need to be considered. Along these lines, priority is suggested to be given to tree planting in degraded or destroyed lands and expanding existing forests [80,144]. This may enhance carbon sequestration and biodiversity while improving the ecosystem's ability to regenerate naturally, thereby positively affecting its resilience [144].

Planting monocultures, often composed solely of non-native tree species, is another example that highlights the importance of thoroughly examining the impacts of afforestation/reforestation. This practice is particularly widespread worldwide, with eucalyptus as well as conifers, primarily pine, and spruce being among the most commonly used species. The highest percentages of monocultures are held, in descending order, by North America, Oceania, Africa, and Asia, where they represent more than 50% of the forested area obtained through afforestation/reforestation [29]. Monocultures offer various advantages, such as rapid growth rates and ease of management, due to their uniformity. Consequently, they are widely used for timber and other forest products, including rubber, paper pulp, charcoal, palm oil, etc. [145]. As a result, they have been associated with local economic development through the exploitation of forest products and services, as well as job creation [146,147]. However, there is evidence suggesting that monocultures do not always have a positive impact on the economy. In several cases, it has been observed that the expansion of these types of forests exacerbates social inequalities and poverty [148,149].

Furthermore, while monocultures are characterized by a rapid carbon sequestration rate, they are likely to cause adverse impacts on soil quality and properties, local flora and fauna, water availability, and forest resilience to extreme weather events, diseases, and pests [2,150–152]. These negative impacts can be further amplified when interventions aimed at enhancing forest biomass productivity, such as thinning, soil fertilization, and harvesting with short rotation lengths, are applied [7]. In recent years, an increasing number of studies have advocated for planting species-rich forests, composed either of native species exclusively or of a combination of non-native and native species. This practice is preferred over monocultures as it promotes biodiversity, exhibits greater resilience, demonstrates better long-term carbon storage performance, enhances the economy, and provides a variety

of socio-environmental benefits [80,144,145,152]. In addition, there is evidence that multi-species plantation positively affects forest productivity, linked to increased forest carbon sequestration [153,154]. In the same vein, according to a recent meta-analysis study, young mixed-planted forests, particularly those consisting of four species, exhibit on average 70% higher aboveground carbon stock accumulation than monocultures [155]. In conclusion, poor planning and inadequate implementation of afforestation/reforestation actions can lead to increases in CO_2 emissions and adverse impacts on humans and ecosystems. Given the diversity of tree species, forest types, regional characteristics, and socio-economic impacts of forests, the implementation of afforestation/reforestation projects requires a multidimensional approach. In this regard, Di Sacco et al. (2021) suggested a set of principles to guide the design of such programs, aiming at achieving optimal outcomes for climate change mitigation, biodiversity preservation, and sustainability at both the local and global scales [144]. In agreement with Seddon et al. (2022), they highlighted the importance of involving indigenous populations and local communities in all phases of afforestation/reforestation from the planning stage to subsequent monitoring [156]. Since indigenous people have an in-depth knowledge of local needs, they can help protect their interests and contribute to the overall success of the project. Additionally, Di Sacco et al., (2021) indicated that successful and sustainable afforestation/reforestation projects require collaboration among all stakeholders (governments, private sector, NGOs, etc.) throughout their lifecycle [144].

Moreover, the benefits arising from afforestation/reforestation for climate change mitigation can be strongly enhanced by combining them with industrial carbon removal technologies, such as Bioenergy with Carbon Capture and Storage (BECCS). BECCS is widely regarded as one of the most promising technologies for reducing greenhouse gas emissions. It involves energy production by biomass combustion, coupled with the capture of the produced CO_2 through carbon capture technologies, and its subsequent storage underground or in geological storage sites [17,78]. Estimates suggest that by 2050, BECCS could remove between 0.5 Gt CO_2 and 5 Gt CO_2 per year [53]. BECCS is typically implemented on an industrial scale and is designed to capture CO_2 emissions from industrial processes, particularly in the energy sector [78]. However, it is important to note that the emissions associated with the lifecycle of BECCS, including CO_2 emissions from land use change, biomass cultivation, harvest, CO_2 capture, transport, and storage, need to be thoroughly considered to accurately assess BECCS's carbon footprint and effectiveness [17].

Nevertheless, combining BECCS with afforestation/reforestation, particularly using fast-growing plantations, enhances the overall carbon removal capacity, making it a viable option for achieving ambitious climate targets. This combination ensures long-term carbon storage and improves land use efficiency by addressing the growth limitations associated with afforestation/reforestation. Moreover, it increases carbon sequestration potential through soil organic carbon over the plantation's lifecycle. Overall, integrating afforestation/reforestation with BECCS can significantly mitigate the challenges associated with their individual applications and establish a robust system for carbon removal from the atmosphere [78].

7. Conclusions

Forests, through their biochemical processes, such as photosynthesis, play a key role in removing CO_2 from the atmosphere and constitute important carbon sinks. However, anthropogenic activities and natural disturbances have resulted in the degradation and destruction of extensive forested areas. Coupled with the looming threat of rapid climate change, the future of forests remains uncertain. Given these challenges, along with the multitude of socio-environmental benefits forests offer and the urgent need for immediate and decisive climate change mitigation actions, afforestation and reforestation programs are gaining steadily increasing attention.

The effectiveness of afforestation/reforestation in addressing climate change depends on various factors, some of which are related to the design and implementation of these actions, whereas others pertain to the characteristics of forests and the impacts of climate change on them. While climate change can enhance forest productivity and carbon sequestration by extending the growing season and accelerating tree growth rates, its benefits are doubtful due to the high spatial variability influenced by regional climatic characteristics, tree species, the magnitude of temperature rise, and the frequency and intensity of forest disturbances. Furthermore, during the development of afforestation/reforestation initiatives, the biophysical mechanisms of the forests also affecting the climate, as well as the potential impacts of land use change, must be taken into account. Consequently, appropriate planning and careful implementation of afforestation and reforestation, tailored to the characteristics of the specific area, along with the adoption of suitable forest management strategies, can maximize the benefits of these programs for climate change mitigation and the environment.

However, despite the pivotal role of forests in CO_2 sequestration, depending solely on afforestation and reforestation initiatives to tackle climate change might not offer a comprehensive solution, considering their limitations and the potential risks and trade-offs involved. For instance, factors such as local climatic conditions, tree species, and age influence their carbon sequestration rates. Forests take time to grow and reach their full carbon sequestration potential. In addition, their capacity to sequester carbon is finite, presenting a decreasing trend with years. Moreover, the availability of land poses a major constraint, as competition with agriculture for food production and land suitability issues limit opportunities for reforestation/afforestation. Furthermore, changing temperature and precipitation patterns, as well as extreme weather events, wildfires, pest outbreaks, and disease spread due to climate change jeopardize carbon storage in forest ecosystems.

Nevertheless, forests possess considerable carbon sequestration potential, leveraging their ability to absorb CO_2 through photosynthesis and store it in biomass and soils. This highlights the vital role forests play in global carbon balance, making afforestation and reforestation crucial components in the fight against climate change. In addition, the combination of these actions with other carbon removal technologies would be beneficial, providing an integrated solution that will increase the likelihood of long-term effectiveness in carbon storage. Overall, effective climate change mitigation demands a comprehensive strategy for both restoring degraded forests and establishing new ones, alongside sustained and intensified endeavors to reduce anthropogenic greenhouse gas emissions.

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References

1. Abbass, K.; Qasim, M.Z.; Song, H.; Murshed, M.; Mahmood, H.; Younis, I. A review of the global climate change impacts, adaptation, and sustainable mitigation measures. *Environ. Sci. Pollut. Res.* **2022**, *29*, 42539–42559. [CrossRef] [PubMed]
2. Seddon, N.; Chausson, A.; Berry, P.; Girardin, C.A.J.; Smith, A.; Turner, B. Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philos. Trans. R. Soc. B Biol. Sci.* **2020**, *375*, 20190120. [CrossRef]
3. Nowak, D.J.; Hirabayashi, S.; Bodine, A.; Greenfield, E. Tree and forest effects on air quality and human health in the United States. *Environ. Pollut.* **2014**, *193*, 119–129. [CrossRef] [PubMed]
4. Zhang, B.; Xie, G.; Li, N.; Wang, S. Effect of urban green space changes on the role of rainwater runoff reduction in Beijing, China. *Landsc. Urban Plan.* **2015**, *140*, 8–16. [CrossRef]
5. Brockerhoff, E.G.; Barbaro, L.; Castagneyrol, B.; Forrester, D.I.; Gardiner, B.; González-Olabarria, J.R.; Lyver, P.O.; Meurisse, N.; Oxbrough, A.; Taki, H.; et al. Forest biodiversity, ecosystem functioning and the provision of ecosystem services. *Biodivers. Conserv.* **2017**, *26*, 3005–3035. [CrossRef]
6. Barrios, E.; Valencia, V.; Jonsson, M.; Brauman, A.; Hairiah, K.; Mortimer, P.E.; Okubo, S. Contribution of trees to the conservation of biodiversity and ecosystem services in agricultural landscapes. *Int. J. Biodivers. Sci. Ecosyst. Serv. Manag.* **2018**, *14*, 1–16. [CrossRef]
7. Sing, L.; Metzger, M.J.; Paterson, J.S.; Ray, D. A review of the effects of forest management intensity on ecosystem services for northern European temperate forests with a focus on the UK. *For. Int. J. For. Res.* **2018**, *91*, 151–164. [CrossRef]
8. Wong, N.H.; Jusuf, S.K.; Syafii, N.I.; Chen, Y.; Hajadi, N.; Sathyanarayanan, H.; Manickavasagam, Y.V. Evaluation of the impact of the surrounding urban morphology on building energy consumption. *Sol. Energy* **2011**, *85*, 57–71. [CrossRef]
9. Gago, E.J.; Roldan, J.; Pacheco-Torres, R.; Ordóñez, J. The city and urban heat islands: A review of strategies to mitigate adverse effects. *Renew. Sustain. Energ. Rev.* **2013**, *25*, 749–758. [CrossRef]
10. Heaviside, C.; Cai, X.; Vardoulakis, S. The effects of horizontal advection on the urban heat island in Birmingham and the West Midlands, United Kingdom during a heatwave. *Q. J. R. Meteorol. Soc.* **2015**, *141*, 1429–1441. [CrossRef]
11. Mantler, A.; Logan, A.C. Natural environments and mental health. *Adv. Integr. Med.* **2015**, *2*, 5–12. [CrossRef]
12. Hall, C.; Knuth, M. An Update of the Literature Supporting the Well-Being Benefits of Plants: A Review of the Emotional and Mental Health Benefits of Plants. *J. Environ. Hortic.* **2019**, *37*, 30–38. [CrossRef]
13. Food and Agriculture Organization of the United Nations (FAO). Global Forest Resources Assessment 2020: Terms and Definitions. Available online: https://www.fao.org/3/I8661EN/i8661en.pdf (accessed on 31 October 2023).
14. Bonan, G.B. Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. *Science* **2008**, *320*, 1444–1449. [CrossRef] [PubMed]
15. Lorenz, K.; Lal, R. *Carbon Sequestration in Forest Ecosystems*; Springer: Berlin/Heidelberg, Germany, 2010. [CrossRef]
16. Baggio-Compagnucci, A.; Ovando, P.; Hewitt, R.J.; Canullo, R.; Gimona, A. Barking up the wrong tree? Can forest expansion help meet climate goals? *Environ. Sci. Policy* **2022**, *136*, 237–249. [CrossRef]
17. Chiquier, S.; Patrizio, P.; Bui, M.; Sunny, N.; Mac Dowell, N. A comparative analysis of the efficiency, timing, and permanence of CO_2 removal pathways. *Energy Environ. Sci.* **2022**, *15*, 4389–4403. [CrossRef]
18. Hoover, K.; Riddle, A.A. Forest Carbon Primer. Congressional Research Service. Available online: https://www.everycrsreport.com/files/20200415_R46312_2693b916ea81d28d80cfebee35043b3d528ec3fb.pdf (accessed on 2 November 2023).
19. Chen, S.; Wang, W.; Xu, W.; Wang, Y.; Wan, H.; Chen, D.; Tang, Z.; Tang, X.; Zhou, G.; Xie, Z.; et al. Plant diversity enhances productivity and soil carbon storage. *Proc. Natl. Acad. Sci. USA* **2018**, *115*, 4027–4032. [CrossRef] [PubMed]
20. He, Y.; Qin, L.; Li, Z.; Liang, X.; Shao, M.; Tan, L. Carbon storage capacity of monoculture and mixed-species plantations in subtropical China. *For. Ecol. Manag.* **2013**, *295*, 193–198. [CrossRef]
21. Li, X.; Ramos Aguila, L.C.; Wu, D.; Lie, Z.; Xu, W.; Tang, X.; Liu, J. Carbon sequestration and storage capacity of Chinese fir at different stand ages. *Sci. Total Environ.* **2023**, *904*, 166962. [CrossRef]
22. Ofiti, N.O.E.; Zosso, C.U.; Soong, J.L.; Solly, E.F.; Torn, M.S.; Wiesenberg, G.L.; Schmidt, M.W. Warming promotes loss of subsoil carbon through accelerated degradation of plant-derived organic matter. *Soil Biol. Biochem.* **2021**, *156*, 108185. [CrossRef]
23. Tyukavina, A.; Baccini, A.; Hansen, M.C.; Potapov, P.V.; Stehman, S.V.; Houghton, R.A.; Krylov, A.M.; Turubanova, S.; Goetz, S.J. Aboveground carbon loss in natural and managed tropical forests from 2000 to 2012. *Environ. Res. Lett.* **2015**, *10*, 074002. [CrossRef]
24. Tong, X.; Brandt, M.; Yue, Y.; Ciais, P.; Rudbeck Jepsen, M.; Penuelas, J.; Wigneron, J.-P.; Xiao, X.-P.; Song, X.-P.; Horion, S.; et al. Forest management in southern China generates short term extensive carbon sequestration. *Nat. Commun.* **2020**, *11*, 129. [CrossRef]
25. Pan, Y.; Birdsey, R.A.; Fang, J.; Houghton, R.; Kauppi, P.E.; Kurz, W.A.; Phillips, O.L.; Shvidenko, A.; Lewis, S.L.; Canadell, J.G.; et al. A large and persistent carbon sink in the world's forests. *Science* **2011**, *333*, 988–993. [CrossRef] [PubMed]
26. Pugh, T.A.M.; Lindeskog, M.; Smith, B.; Poulter, B.; Arneth, A.; Haverd, V.; Calle, L. Role of forest regrowth in global carbon sink dynamics. *Proc. Natl. Acad. Sci. USA* **2019**, *116*, 4382–4387. [CrossRef] [PubMed]
27. Harris, N.L.; Gibbs, D.A.; Baccini, A.; Birdsey, R.A.; de Bruin, S.; Farina, M.; Fatoyinbo, L.; Hansen, M.C.; Herold, M.; Houghton, R.A.; et al. Global maps of twenty-first century forest carbon fluxes. *Nat. Clim. Chang.* **2021**, *11*, 234–240. [CrossRef]
28. Zhao, J.; Xie, H.; Ma, J.; Wang, K. Integrated remote sensing and model approach for impact assessment of future climate change on the carbon budget of global forest ecosystems. *Glob. Planet. Chang.* **2021**, *203*, 103542. [CrossRef]

29. Food and Agriculture Organization of the United Nations (FAO). *Global Forest Resources Assessment 2020: Main Report*; FAO: Rome, Italy, 2020. [CrossRef]
30. Federici, S.; Tubiello, F.N.; Salvatore, M.; Jacobs, H.; Schmidhuber, J. New estimates of CO_2 forest emissions and removals: 1990–2015. *For. Ecol. Manag.* **2015**, *352*, 89–98. [CrossRef]
31. Tubiello, F.N.; Conchedda, G.; Wanner, N.; Federici, S.; Rossi, S.; Grassi, G. Carbon emissions and removals from forests: New estimates, 1990–2020. *Earth Syst. Sci. Data* **2021**, *13*, 1681–1691. [CrossRef]
32. Li, Y.; Zhou, L.; Wang, S.; Chi, Y.; Chen, J. Leaf Temperature and Vapour Pressure Deficit (VPD) Driving Stomatal Conductance and Biochemical Processes of Leaf Photosynthetic Rate in a Subtropical Evergreen Coniferous Plantation. *Sustainability* **2018**, *10*, 4063. [CrossRef]
33. Dusenge, M.E.; Duarte, A.G.; Way, D.A. Plant carbon metabolism and climate change: Elevated CO_2 and temperature impacts on photosynthesis, photorespiration and respiration. *New Phytol.* **2019**, *221*, 32–49. [CrossRef]
34. Crous, K.Y.; Uddling, J.; De Kauwe, M.G. Temperature responses of photosynthesis and respiration in evergreen trees from boreal to tropical latitudes. *New Phytol.* **2022**, *234*, 353–374. [CrossRef]
35. Grossiord, C.; Buckley, T.N.; Cernusak, L.A.; Novick, K.A.; Poulter, B.; Siegwolf, R.T.W.; Sperry, J.S.; McDowell, N.G. Plant responses to rising vapor pressure deficit. *New Phytol.* **2020**, *226*, 1550–1566. [CrossRef]
36. Friedlingstein, P.; O'sullivan, M.; Jones, M.W.; Andrew, R.M.; Gregor, L.; Hauck, J.; Le Quéré, C.; Luijkx, I.T.; Olsen, A.; Peters, G.P.; et al. Global carbon budget 2022. *Earth Syst. Sci. Data* **2022**, *14*, 4811–4900. [CrossRef]
37. Feng, H.; Wang, S.; Zou, B.; Yang, Z.; Wang, S.; Wang, W. Contribution of land use and cover change (LUCC) to the global terrestrial carbon uptake. *Sci. Total Environ.* **2023**, *901*, 165932. [CrossRef]
38. Jackson, R.B.; Randerson, J.T.; Canadell, J.G.; Anderson, R.G.; Avissar, R.; Baldocchi, D.D.; Bonan, G.B.; Caldeira, K.; Diffenbaugh, N.S.; Field, C.B.; et al. Protecting climate with forests. *Environ. Res. Lett.* **2008**, *3*, 044006. [CrossRef]
39. Li, Y.; Zhao, M.; Motesharrei, S.; Mu, Q.; Kalnay, E.; Li, S. Local cooling and warming effects of forests based on satellite observations. *Nat. Commun.* **2015**, *6*, 6603. [CrossRef]
40. Bright, R.M.; Zhao, K.; Jackson, R.B.; Cherubini, F. Quantifying surface albedo and other direct biogeophysical climate forcings of forestry activities. *Glob. Chang. Biol.* **2015**, *21*, 3246–3266. [CrossRef] [PubMed]
41. Griscom, B.W.; Adams, J.; Ellis, P.W.; Houghton, R.A.; Lomax, G.; Miteva, D.A.; Schlesinger, W.H.; Shoch, D.; Siikamäki, J.V.; Smith, P.; et al. Natural climate solutions. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 11645–11650. [CrossRef]
42. Williams, C.A.; Gu, H.; Jiao, T. Climate impacts of U.S. forest loss span net warming to net cooling. *Sci. Adv.* **2021**, *7*, eaax8859. [CrossRef] [PubMed]
43. Breil, M.; Krawczyk, F.; Pinto, J.G. The response of the regional longwave radiation balance and climate system in Europe to an idealized afforestation experiment. *Earth Syst. Dyn.* **2023**, *14*, 243–253. [CrossRef]
44. Anderson-Teixeira, K.J.; Snyder, P.K.; Twine, T.E.; Cuadra, S.V.; Costa, M.H.; DeLucia, E.H. Climate-regulation services of natural and agricultural ecoregions of the Americas. *Nat. Clim. Chang.* **2012**, *2*, 177–181. [CrossRef]
45. Baker, J.C.A.; Spracklen, D.V. Climate Benefits of Intact Amazon Forests and the Biophysical Consequences of Disturbance. *Front. For. Glob. Chang.* **2019**, *2*, 47. [CrossRef]
46. Alkama, R.; Cescatti, A. Biophysical climate impacts of recent changes in global forest cover. *Science* **2016**, *351*, 600–604. [CrossRef]
47. Wickham, J.D.; Wade, T.G.; Riitters, K.H. Empirical analysis of the influence of forest extent on annual and seasonal surface temperatures for the continental United States. *Glob. Ecol. Biogeogr.* **2013**, *22*, 620–629. [CrossRef]
48. Lyra, A.; Imbach, P.; Rodriguez, D.; Chou, S.C.; Georgiou, S.; Garofolo, L. Projections of climate change impacts on Central America tropical rainforest. *Clim. Chang.* **2017**, *141*, 93–105. [CrossRef]
49. Pugh, T.A.M.; Arneth, A.; Kautz, M.; Poulter, B.; Smith, B. Important role of forest disturbances in the global biomass turnover and carbon sinks. *Nat. Geosci.* **2019**, *12*, 730–735. [CrossRef]
50. Mitchard, E.T.A. The tropical forest carbon cycle and climate change. *Nature* **2018**, *559*, 527–534. [CrossRef]
51. Anderegg, W.R.L.; Trugman, A.T.; Badgley, G.; Anderson, C.M.; Bartuska, A.; Ciais, P.; Cullenward, D.; Field, C.B.; Freeman, J.; Goetz, S.J.; et al. Climate-driven risks to the climate mitigation potential of forests. *Science* **2020**, *368*, eaaz7005. [CrossRef] [PubMed]
52. Halofsky, J.E.; Peterson, D.L.; Harvey, B.J. Changing wildfire, changing forests: The effects of climate change on fire regimes and vegetation in the Pacific Northwest, USA. *Fire Ecol.* **2020**, *16*, 4. [CrossRef]
53. Fuss, S.; Lamb, W.F.; Callaghan, M.W.; Hilaire, J.; Creutzig, F.; Amann, T.; Beringer, T.; Garcia, W.d.O.; Hartmann, J.; Khanna, T.; et al. Negative emissions—Part 2: Costs, potentials and side effects. *Environ. Res. Lett.* **2018**, *13*, 063002. [CrossRef]
54. Yang, Y.; Saatchi, S.S.; Xu, L.; Yu, Y.; Choi, S.; Phillips, N.; Kennedy, R.; Keller, M.; Knyazikhin, Y.; Myneni, R.B. Post-drought decline of the Amazon carbon sink. *Nat. Commun.* **2018**, *9*, 3172. [CrossRef] [PubMed]
55. Zarin, D.J.; Harris, N.L.; Baccini, A.; Aksenov, D.; Hansen, M.C.; Azevedo-Ramos, C.; Azevedo, T.; Margono, B.A.; Alencar, A.C.; Gabris, C.; et al. Can carbon emissions from tropical deforestation drop by 50% in 5 years? *Glob. Chang. Biol.* **2016**, *22*, 1336–1347. [CrossRef] [PubMed]
56. Pearson, T.R.H.; Brown, S.; Murray, L.; Sidman, G. Greenhouse gas emissions from tropical forest degradation: An underestimated source. *Carbon Balance Manag.* **2017**, *12*, 3. [CrossRef] [PubMed]
57. Pausas, J.G.; Keeley, J.E. Wildfires as an ecosystem service. *Front. Ecol. Environ.* **2019**, *17*, 289–295. [CrossRef]

58. McLauchlan, K.K.; Higuera, P.E.; Miesel, J.; Rogers, B.M.; Schweitzer, J.; Shuman, J.K.; Tepley, A.J.; Varner, J.M.; Veblen, T.T.; Adalsteinsson, S.A.; et al. Fire as a fundamental ecological process: Research advances and frontiers. *J. Ecol.* **2020**, *108*, 2047–2069. [CrossRef]
59. van Lierop, P.; Lindquist, E.; Sathyapala, S.; Franceschini, G. Global forest area disturbance from fire, insect pests, diseases and severe weather events. *For. Ecol. Manag.* **2015**, *352*, 78–88. [CrossRef]
60. Abatzoglou, J.T.; Williams, A.P.; Boschetti, L.; Zubkova, M.; Kolden, C.A. Global patterns of interannual climate–fire relationships. *Glob. Chang. Biol.* **2018**, *24*, 5164–5175. [CrossRef] [PubMed]
61. Zheng, B.; Ciais, P.; Chevallier, F.; Chuvieco, E.; Chen, Y.; Yang, H. Increasing forest fire emissions despite the decline in global burned area. *Sci. Adv.* **2021**, *7*, eabh2646. [CrossRef] [PubMed]
62. Zhao, B.; Zhuang, Q.; Shurpali, N.; Köster, K.; Berninger, F.; Pumpanen, J. North American boreal forests are a large carbon source due to wildfires from 1986 to 2016. *Sci. Rep.* **2021**, *11*, 7723. [CrossRef]
63. Ponomarev, E.; Yakimov, N.; Ponomareva, T.; Yakubailik, O.; Conard, S.G. Current Trend of Carbon Emissions from Wildfires in Siberia. *Atmosphere* **2021**, *12*, 559. [CrossRef]
64. van der Velde, I.R.; van der Werf, G.R.; Houweling, S.; Maasakkers, J.D.; Borsdorff, T.; Landgraf, J.; Tol, P.; van Kempen, T.A.; van Hees, R.; Hoogeveen, R.; et al. Vast CO_2 release from Australian fires in 2019–2020 constrained by satellite. *Nature* **2021**, *597*, 366–369. [CrossRef]
65. MacCarthy, J.; Tyukavina, A.; Weisse, M.J.; Harris, N.; Glen, E. Extreme wildfires in Canada and their contribution to global loss in tree cover and carbon emissions in 2023. *Glob. Chang. Biol.* **2024**, *30*, e17392. [CrossRef] [PubMed]
66. Di Virgilio, G.; Evans, J.P.; Blake, S.A.P.; Armstrong, M.; Dowdy, A.J.; Sharples, J.; McRae, R. Climate Change Increases the Potential for Extreme Wildfires. *Geophys. Res. Lett.* **2019**, *46*, 8517–8526. [CrossRef]
67. Dupuy, J.-L.; Fargeon, H.; Martin-StPaul, N.; Pimont, F.; Ruffault, J.; Guijarro, M.; Hernando, C.; Madrigal, J.; Fernandes, P. Climate change impact on future wildfire danger and activity in southern Europe: A review. *Ann. For. Sci.* **2020**, *77*, 35. [CrossRef]
68. Ruffault, J.; Curt, T.; Moron, V.; Trigo, R.M.; Mouillot, F.; Koutsias, N.; Pimont, F.; Martin-StPaul, N.; Barbero, R.; Dupuy, J.-L.; et al. Increased likelihood of heat-induced large wildfires in the Mediterranean Basin. *Sci. Rep.* **2020**, *10*, 13790. [CrossRef] [PubMed]
69. Rovithakis, A.; Grillakis, M.G.; Seiradakis, K.D.; Giannakopoulos, C.; Karali, A.; Field, R.; Lazaridis, M.; Voulgarakis, A. Future climate change impact on wildfire danger over the Mediterranean: The case of Greece. *Environ. Res. Lett.* **2022**, *17*, 045022. [CrossRef]
70. He, T.; Lamont, B.B.; Pausas, J.G. Fire as a key driver of Earth's biodiversity. *Biol. Rev.* **2019**, *94*, 1983–2010. [CrossRef] [PubMed]
71. Cui, W.; Perera, A.H. What do we know about forest fire size distribution, and why is this knowledge useful for forest management? *Int. J. Wildland Fire* **2008**, *17*, 234–244. [CrossRef]
72. Moreira, F.; Ascoli, D.; Safford, H.; Adams, M.A.; Moreno, J.M.; Pereira, J.M.C.; Catry, F.X.; Armesto, J.; Bond, W.; González, M.E.; et al. Wildfire management in Mediterranean-type regions: Paradigm change needed. *Environ. Res. Lett.* **2020**, *15*, 011001. [CrossRef]
73. Parisien, M.-A.; Barber, Q.E.; Hirsch, K.G.; Stockdale, C.A.; Erni, S.; Wang, X.; Arseneault, D.; Parks, S.A. Fire deficit increases wildfire risk for many communities in the Canadian boreal forest. *Nat. Commun.* **2020**, *11*, 2121. [CrossRef]
74. Roe, S.; Streck, C.; Obersteiner, M.; Frank, S.; Griscom, B.; Drouet, L.; Fricko, O.; Gusti, M.; Harris, N.; Hasegawa, T.; et al. Contribution of the land sector to a 1.5 °C world. *Nat. Clim. Chang.* **2019**, *9*, 817–828. [CrossRef]
75. Bastin, J.-F.; Finegold, Y.; Garcia, C.; Mollicone, D.; Rezende, M.; Routh, D.; Zohner, C.M.; Crowther, T.W. The global tree restoration potential. *Science* **2019**, *365*, 76–79. [CrossRef]
76. Raihan, A.; Begum, R.A.; Said, M.N.M.; Abdullah, S.M.S. A Review of Emission Reduction Potential and Cost Savings through Forest Carbon Sequestration. *Asian J. Water, Environ. Pollut.* **2019**, *16*, 1–7. [CrossRef]
77. Mayer, M.; Prescott, C.E.; Abaker, W.E.A.; Augusto, L.; Cécillon, L.; Ferreira, G.W.; James, J.; Jandl, R.; Katzensteiner, K.; Laclau, J.-P.; et al. Tamm Review: Influence of forest management activities on soil organic carbon stocks: A knowledge synthesis. *For. Ecol. Manag.* **2020**, *466*, 118127. [CrossRef]
78. Osman, A.I.; Fawzy, S.; Lichtfouse, E.; Rooney, D.W. Planting trees to combat global warming. *Environ. Chem. Lett.* **2023**, *21*, 3041–3044. [CrossRef]
79. Lewis, S.L.; Mitchard, E.T.A.; Prentice, C.; Maslin, M.; Poulter, B. Comment on "The global tree restoration potential". *Science* **2019**, *366*, eaaz0388. [CrossRef]
80. Doelman, J.C.; Stehfest, E.; van Vuuren, D.P.; Tabeau, A.; Hof, A.F.; Braakhekke, M.C.; Gernaat, D.E.H.J.; Berg, M.v.D.; van Zeist, W.; Daioglou, V.; et al. Afforestation for climate change mitigation: Potentials, risks and trade-offs. *Glob. Chang. Biol.* **2019**, *26*, 1576–1591. [CrossRef] [PubMed]
81. Wang, S.; Huang, Y. Determinants of soil organic carbon sequestration and its contribution to ecosystem carbon sinks of planted forests. *Glob. Chang. Biol.* **2020**, *26*, 3163–3173. [CrossRef] [PubMed]
82. United Nations Framework Convention on Climate Change (UNFCCC). *Report of the Conference of the Parties on its Seventh Session, Held in Marrakech from 29 October to 10 November 2001. Addendum Part Two: Action Taken by the Conference of the Parties*; FCCC/CP/2001/13/Add. 1; United Nations Framework Convention on Climate Change Secretariat: Bonn, Germany, 2002; Volume I.
83. Houghton, R.A.; Byers, B.; Nassikas, A.A. A role for tropical forests in stabilizing atmospheric CO_2. *Nat. Clim. Chang.* **2015**, *5*, 1022–1023. [CrossRef]

84. Ménard, I.; Thiffault, E.; Kurz, W.A.; Boucher, J.-F. Carbon sequestration and emission mitigation potential of afforestation and reforestation of unproductive territories. *New For.* **2023**, *54*, 1013–1035. [CrossRef]
85. McPhearson, P.T.; Feller, M.; Felson, A.; Karty, R.; Lu, J.W.; Palmer, M.I.; Wenskus, T. Assessing the effects of the urban forest restoration effect of MillionTreesNYC on the structure and functioning of New York City ecosystems. *Cities Environ.* **2011**, *3*, 7. [CrossRef]
86. McPherson, E.G.; Simpson, J.R.; Xiao, Q.; Wu, C. Million trees Los Angeles canopy cover and benefit assessment. *Landsc. Urban Plan.* **2011**, *99*, 40–50. [CrossRef]
87. Yao, N.; Konijnendijk van den Bosch, C.C.; Yang, J.; Devisscher, T.; Wirtz, Z.; Jia, L.; Duan, J.; Ma, L. Beijing's 50 million new urban trees: Strategic governance for large-scale urban afforestation. *Urban For. Urban Green.* **2019**, *44*, 126392. [CrossRef]
88. Teo, H.C.; Zeng, Y.; Sarira, T.V.; Fung, T.K.; Zheng, Q.; Song, X.P.; Chong, K.Y.; Koh, L.P. Global urban reforestation can be an important natural climate solution. *Environ. Res. Lett.* **2021**, *16*, 034059. [CrossRef]
89. Friedlingstein, P.; Allen, M.; Canadell, J.G.; Peters, G.P.; Seneviratne, S.I. Comment on "The global tree restoration potential". *Science* **2019**, *366*, eaay8060. [CrossRef]
90. Veldman, J.W.; Aleman, J.C.; Alvarado, S.T.; Anderson, T.M.; Archibald, S.; Bond, W.J.; Boutton, T.W.; Buchmann, N.; Buisson, E.; Canadell, J.G.; et al. Comment on "The global tree restoration potential". *Science* **2019**, *366*, eaay7976. [CrossRef]
91. Taylor, S.D.; Marconi, S. Rethinking global carbon storage potential of trees. A comment on Bastin et al. (2019). *Ann. For. Sci.* **2020**, *77*, 23. [CrossRef]
92. Delzeit, R.; Pongratz, J.; Schneider, J.M.; Schuenemann, F.; Mauser, W.; Zabel, F. Forest restoration: Expanding agriculture. *Science* **2019**, *366*, 316–317. [CrossRef]
93. Kreidenweis, U.; Humpenöder, F.; Stevanović, M.; Bodirsky, B.L.; Kriegler, E.; Lotze-Campen, H.; Popp, A. Afforestation to mitigate climate change: Impacts on food prices under consideration of albedo effects. *Environ. Res. Lett.* **2016**, *11*, 085001. [CrossRef]
94. Frank, S.; Havlík, P.; Soussana, J.-F.; Levesque, A.; Valin, H.; Wollenberg, E.; Kleinwechter, U.; Fricko, O.; Gusti, M.; Herrero, M.; et al. Reducing greenhouse gas emissions in agriculture without compromising food security? *Environ. Res. Lett.* **2017**, *12*, 105004. [CrossRef]
95. Hasegawa, T.; Fujimori, S.; Shin, Y.; Tanaka, A.; Takahashi, K.; Masui, T. Consequence of climate mitigation on the risk of hunger. *Environ. Sci. Technol.* **2015**, *49*, 7245–7253. [CrossRef] [PubMed]
96. Hasegawa, T.; Fujimori, S.; Havlík, P.; Valin, H.; Bodirsky, B.L.; Doelman, J.C.; Fellmann, T.; Kyle, P.; Koopman, J.F.L.; Lotze-Campen, H.; et al. Risk of increased food insecurity under stringent global climate change mitigation policy. *Nat. Clim. Chang.* **2018**, *8*, 699–703. [CrossRef]
97. Fujimori, S.; Wu, W.; Doelman, J.; Frank, S.; Hristov, J.; Kyle, P.; Sands, R.; van Zeist, W.-J.; Havlik, P.; Domínguez, I.P.; et al. Land-based climate change mitigation measures can affect agricultural markets and food security. *Nat. Food* **2022**, *3*, 110–121. [CrossRef] [PubMed]
98. Fagan, M.E.; Reid, J.L.; Holland, M.B.; Drew, J.G.; Zahawi, R.A. How feasible are global forest restoration commitments? *Conserv. Lett.* **2020**, *13*, e12700. [CrossRef]
99. Waldron, A.; Garrity, D.; Malhi, Y.; Girardin, C.; Miller, D.C.; Seddon, N. Agroforestry Can Enhance Food Security While Meeting Other Sustainable Development Goals. *Trop. Conserv. Sci.* **2017**, *10*. [CrossRef]
100. Pantera, A.; Mosquera-Losada, M.R.; Herzog, F.; Herder, M.D. Agroforestry and the environment. *Agrofor. Syst.* **2021**, *95*, 767–774. [CrossRef]
101. Cardinael, R.; Cadisch, G.; Gosme, M.; Oelbermann, M.; van Noordwijk, M. Climate change mitigation and adaptation in agriculture: Why agroforestry should be part of the solution. *Agric. Ecosyst. Environ.* **2021**, *319*, 107555. [CrossRef]
102. Pérez-Cruzado, C.; Mansilla-Salinero, P.; Rodríguez-Soalleiro, R.; Merino, A. Influence of tree species on carbon sequestration in afforested pastures in a humid temperate region. *Plant Soil* **2012**, *353*, 333–353. [CrossRef]
103. Vesterdal, L.; Clarke, N.; Sigurdsson, B.D.; Gundersen, P. Do tree species influence soil carbon stocks in temperate and boreal forests? *For. Ecol. Manag.* **2013**, *309*, 4–18. [CrossRef]
104. Liu, Y.; Yu, G.; Wang, Q.; Zhang, Y. How temperature, precipitation and stand age control the biomass carbon density of global mature forests. *Glob. Ecol. Biogeogr.* **2014**, *23*, 323–333. [CrossRef]
105. Barré, P.; Quénéa, K.; Vidal, A.; Cécillon, L.; Christensen, B.T.; Kätterer, T.; Macdonald, A.; Petit, L.; Plante, A.F.; van Oort, F.; et al. Microbial and plant-derived compounds both contribute to persistent soil organic carbon in temperate soils. *Biogeochemistry* **2018**, *140*, 81–92. [CrossRef]
106. Hofhansl, F.; Chacón-Madrigal, E.; Fuchslueger, L.; Jenking, D.; Morera-Beita, A.; Plutzar, C.; Silla, F.; Andersen, K.M.; Buchs, D.M.; Dullinger, S.; et al. Climatic and edaphic controls over tropical forest diversity and vegetation carbon storage. *Sci. Rep.* **2020**, *10*, 5066. [CrossRef] [PubMed]
107. Ming, A.; Jia, H.; Zhao, J.; Tao, Y.; Li, Y. Above- and below-ground carbon stocks in an indigenous tree (*Mytilaria laosensis*) plantation chronosequence in subtropical China. *PLoS ONE* **2014**, *9*, e109730. [CrossRef] [PubMed]
108. Bernal, B.; Murray, L.T.; Pearson, T.R.H. Global carbon dioxide removal rates from forest landscape restoration activities. *Carbon Balance Manag.* **2018**, *13*, 22. [CrossRef] [PubMed]
109. Balima, L.H.; Kouamé, F.N.; Bayen, P.; Ganamé, M.; Nacoulma, B.M.I.; Thiombiano, A.; Soro, D. Influence of climate and forest attributes on aboveground carbon storage in Burkina Faso, West Africa. *Environ. Chall.* **2021**, *4*, 100123. [CrossRef]

110. Wen, D.; He, N. Forest carbon storage along the north-south transect of eastern China: Spatial patterns, allocation, and influencing factors. *Ecol. Indic.* **2016**, *61*, 960–967. [CrossRef]
111. Etzold, S.; Waldner, P.; Thimonier, A.; Schmitt, M.; Dobbertin, M. Tree growth in Swiss forests between 1995 and 2010 in relation to climate and stand conditions: Recent disturbances matter. *For. Ecol. Manag.* **2014**, *311*, 41–55. [CrossRef]
112. Koulelis, P.P.; Daskalakou, E.N.; Ioannidis, K.E. Impact of regional climatic conditions on tree growth on mainland Greece. *Folia Oecologica* **2019**, *46*, 127–136. [CrossRef]
113. Osei, R.; del Río, M.; Ruiz-Peinado, R.; Titeux, H.; Bielak, K.; Bravo, F.; Collet, C.; Cools, C.; Cornelis, J.-T.; Drössler, L.; et al. The distribution of carbon stocks between tree woody biomass and soil differs between Scots pine and broadleaved species (beech, oak) in European forests. *Eur. J. For. Res.* **2022**, *141*, 467–480. [CrossRef] [PubMed]
114. Węgiel, A.; Polowy, K. Aboveground carbon content and storage in mature scots pine stands of different densities. *Forests* **2020**, *11*, 240. [CrossRef]
115. Na, M.; Sun, X.; Zhang, Y.; Sun, Z.; Rousk, J. Higher stand densities can promote soil carbon storage after conversion of temperate mixed natural forests to larch plantations. *Eur. J. For. Res.* **2021**, *140*, 373–386. [CrossRef]
116. Langenbruch, C.; Helfrich, M.; Flessa, H. Effects of beech (*Fagus sylvatica*), ash (*Fraxinus excelsior*) and lime (*Tilia* spec.) on soil chemical properties in a mixed deciduous forest. *Plant Soil* **2012**, *352*, 389–403. [CrossRef]
117. Boča, A.; Van Miegroet, H.; Gruselle, M.-C. Forest overstory effect on soil organic carbon storage: A meta-analysis. *Soil Sci. Soc. Am. J.* **2014**, *78*, S35–S47. [CrossRef]
118. Cha, J.-Y.; Cha, Y.; Oh, N.-H. The Effects of Tree Species on Soil Organic Carbon Content in South Korea. *J. Geophys. Res. Biogeosciences* **2019**, *124*, 708–716. [CrossRef]
119. Mueller, K.E.; Eissenstat, D.M.; Hobbie, S.E.; Oleksyn, J.; Jagodzinski, A.M.; Reich, P.B.; Chadwick, O.A.; Chorover, J. Tree species effects on coupled cycles of carbon, nitrogen, and acidity in mineral soils at a common garden experiment. *Biogeochemistry* **2012**, *111*, 601–614. [CrossRef]
120. Frouz, J.; Livečková, M.; Albrechtová, J.; Chroňáková, A.; Cajthaml, T.; Pižl, V.; Háněl, L.; Starý, J.; Baldrian, P.; Lhotáková, Z.; et al. Is the effect of trees on soil properties mediated by soil fauna? A case study from post-mining sites. *For. Ecol. Manag.* **2013**, *309*, 87–95. [CrossRef]
121. Prescott, C.E.; Grayston, S.J. Tree species influence on microbial communities in litter and soil: Current knowledge and research needs. *For. Ecol. Manag.* **2013**, *309*, 19–27. [CrossRef]
122. Wiesmeier, M.; Urbanski, L.; Hobley, E.; Lang, B.; von Lützow, M.; Marin-Spiotta, E.; van Wesemael, B.; Rabot, E.; Ließ, M.; Garcia-Franco, N.; et al. Soil organic carbon storage as a key function of soils—A review of drivers and indicators at various scales. *Geoderma* **2019**, *333*, 149–162. [CrossRef]
123. Chen, X.; Taylor, A.R.; Reich, P.B.; Hisano, M.; Chen, H.Y.H.; Chang, S.X. Tree diversity increases decadal forest soil carbon and nitrogen accrual. *Nature* **2023**, *618*, 94–101. [CrossRef]
124. Osei, R.; Titeux, H.; Bielak, K.; Bravo, F.; Collet, C.; Cools, C.; Cornelis, J.-T.; Heym, M.; Korboulewsky, N.; Löf, M.; et al. Tree species identity drives soil organic carbon storage more than species mixing in major two-species mixtures (pine, oak, beech) in Europe. *For. Ecol. Manag.* **2021**, *481*, 118752. [CrossRef]
125. Crossman, N.D.; Bryan, B.A.; Summers, D.M. Carbon payments and low-cost conservation. *Conserv. Biol.* **2011**, *25*, 835–845. [CrossRef]
126. CSIRO. *Australian National Outlook*; CSIRO: Canberra, Australia, 2019.
127. Hou, G.; Delang, C.O.; Lu, X.; Olschewski, R. Optimizing rotation periods of forest plantations: The effects of carbon accounting regimes. *For. Policy Econ.* **2020**, *118*, 102263. [CrossRef]
128. Hulvey, K.B.; Hobbs, R.J.; Standish, R.J.; Lindenmayer, D.B.; Lach, L.; Perring, M.P. Benefits of tree mixes in carbon plantings. *Nat. Clim. Chang.* **2013**, *3*, 869–874. [CrossRef]
129. Castro-Izaguirre, N.; Chi, X.; Baruffol, M.; Tang, Z.; Ma, K.; Schmid, B.; Niklaus, P.A. Tree Diversity Enhances Stand Carbon Storage but Not Leaf Area in a Subtropical Forest. *PLoS ONE* **2016**, *11*, e0167771. [CrossRef]
130. McNicol, I.M.; Ryan, C.M.; Dexter, K.G.; Ball, S.M.J.; Williams, M. Aboveground Carbon Storage and Its Links to Stand Structure, Tree Diversity and Floristic Composition in South-Eastern Tanzania. *Ecosystems* **2018**, *21*, 740–754. [CrossRef]
131. Standish, R.J.; Prober, S.M. Potential benefits of biodiversity to Australian vegetation projects registered with the Emissions Reduction Fund—Is there a carbon-biodiversity trade-off? *Ecol. Manag. Restor.* **2020**, *21*, 165–172. [CrossRef]
132. Dawud, S.M.; Raulund-Rasmussen, K.; Domisch, T.; Finér, L.; Jaroszewicz, B.; Vesterdal, L. Is tree species diversity or species identity the more important driver of soil carbon stocks, C/N ratio, and pH? *Ecosystems* **2016**, *19*, 645–660. [CrossRef]
133. Karhu, K.; Wall, A.; Vanhala, P.; Liski, J.; Esala, M.; Regina, K. Effects of afforestation and deforestation on boreal soil carbon stocks—Comparison of measured C stocks with Yasso07 model results. *Geoderma* **2011**, *164*, 33–45. [CrossRef]
134. Frouz, J.; Vindušková, O. Soil Organic Matter Accumulation in Postmining Sites: Potential Drivers and Mechanisms. In *Soil Management and Climate Change*; Muñoz, M.Á., Zornoza, R., Eds.; Academic Press: Cambridge, MA, USA, 2018; pp. 103–120. [CrossRef]
135. Friggens, N.L.; Hester, A.J.; Mitchell, R.J.; Parker, T.C.; Subke, J.; Wookey, P.A. Tree planting in organic soils does not result in net carbon sequestration on decadal timescales. *Glob. Chang. Biol.* **2020**, *26*, 5178–5188. [CrossRef]
136. Hüblová, L.; Frouz, J. Contrasting effect of coniferous and broadleaf trees on soil carbon storage during reforestation of forest soils and afforestation of agricultural and post-mining soils. *J. Environ. Manag.* **2021**, *290*, 112567. [CrossRef]

137. Venäläinen, A.; Lehtonen, I.; Laapas, M.; Ruosteenoja, K.; Tikkanen, O.-P.; Viiri, H.; Ikonen, V.; Peltola, H. Climate change induces multiple risks to boreal forests and forestry in Finland: A literature review. *Glob. Chang. Biol.* **2020**, *26*, 4178–4196. [CrossRef]
138. D'Orangeville, L.; Houle, D.; Duchesne, L.; Phillips, R.P.; Bergeron, Y.; Kneeshaw, D. Beneficial effects of climate warming on boreal tree growth may be transitory. *Nat. Commun.* **2018**, *9*, 3213. [CrossRef] [PubMed]
139. Walentowski, H.; Falk, W.; Mette, T.; Kunz, J.; Bräuning, A.; Meinardus, C.; Zang, C.; Sutcliffe, L.M.; Leuschner, C. Assessing future suitability of tree species under climate change by multiple methods: A case study in southern Germany. *Ann. For. Res.* **2017**, *60*, 101–126. [CrossRef]
140. MacKenzie, W.H.; Mahony, C.R. An ecological approach to climate change-informed tree species selection for reforestation. *For. Ecol. Manag.* **2021**, *481*, 118705. [CrossRef]
141. Millar, C.I.; Stephenson, N.L. Temperate forest health in an era of emerging megadisturbance. *Science* **2015**, *349*, 823–826. [CrossRef] [PubMed]
142. Schwärzel, K.; Zhang, L.; Montanarella, L.; Wang, Y.; Sun, G. How afforestation affects the water cycle in drylands: A process-based comparative analysis. *Glob. Chang. Biol.* **2020**, *26*, 944–959. [CrossRef] [PubMed]
143. Zhang, T.; Yang, J.; Winrich, A.; Will, R.E.; Zou, C.B. Trade-off of ecosystem productivity and water use related to afforestation in southcentral USA under climate change. *Sci. Total Environ.* **2024**, *915*, 170255. [CrossRef] [PubMed]
144. Di Sacco, A.; Hardwick, K.A.; Blakesley, D.; Brancalion, P.H.S.; Breman, E.; Cecilio Rebola, L.; Chomba, S.; Dixon, K.; Elliott, S.; Ruyonga, G.; et al. Ten golden rules for reforestation to optimize carbon sequestration, biodiversity recovery and livelihood benefits. *Glob. Chang. Biol.* **2021**, *27*, 1328–1348. [CrossRef]
145. Liu, C.L.C.; Kuchma, O.; Krutovsky, K.V. Mixed-species versus monocultures in plantation forestry: Development, benefits, ecosystem services and perspectives for the future. *Glob. Ecol. Conserv.* **2018**, *15*, e00419. [CrossRef]
146. Ying, Z.; Irland, L.; Zhou, X.; Song, Y.; Wen, Y.; Liu, J.; Song, W.; Qiu, Y. Plantation development: Economic analysis of forest management in Fujian province, China. *For. Policy Econ.* **2010**, *12*, 223–230. [CrossRef]
147. Nambiar, E.K.S.; Harwood, C.E.; Kien, N.D. *Acacia* plantations in Vietnam: Research and knowledge application to secure a sustainable future. *South. For.* **2015**, *77*, 1–10. [CrossRef]
148. Malkamäki, A.; D'Amato, D.; Hogarth, N.J.; Kanninen, M.; Pirard, R.; Toppinen, A.; Zhou, W. A systematic review of the socio-economic impacts of large-scale tree plantations, worldwide. *Glob. Environ. Chang.* **2018**, *53*, 90–103. [CrossRef]
149. Hofflinger, A.; Nahuelpan, H.; Boso, À.; Millalen, P. Do Large-Scale Forestry Companies Generate Prosperity in Indigenous Communities? The Socioeconomic Impacts of Tree Plantations in Southern Chile. *Hum. Ecol.* **2021**, *49*, 619–630. [CrossRef]
150. Jactel, H.; Bauhus, J.; Boberg, J.; Bonal, D.; Castagneyrol, B.; Gardiner, B.; Gonzalez-Olabarria, J.R.; Koricheva, J.; Meurisse, N.; Brockerhoff, E.G. Tree diversity drives forest stand resistance to natural disturbances. *Curr. For. Rep.* **2017**, *3*, 223–243. [CrossRef]
151. Hong, W.; Yang, J.; Luo, J.; Jiang, K.; Xu, J.; Zhang, H. Reforestation Based on Mono-Plantation of Fast-Growing Tree Species Make It Difficult to Maintain (High) Soil Water Content in Tropics, a Case Study in Hainan Island, China. *Water* **2020**, *12*, 3077. [CrossRef]
152. Pinnschmidt, A.; Yousefpour, R.; Nölte, A.; Hanewinkel, M. Tropical mixed-species plantations can outperform monocultures in terms of carbon sequestration and economic return. *Ecol. Econ.* **2023**, *211*, 107885. [CrossRef]
153. Liang, J.; Crowther, T.W.; Picard, N.; Wiser, S.; Zhou, M.; Alberti, G.; Schulze, E.-D.; McGuire, A.D.; Bozzato, F.; Pretzsch, H.; et al. Positive biodiversity-productivity relationship predominant in global forests. *Science* **2016**, *354*, aaf8957. [CrossRef] [PubMed]
154. Feng, Y.; Schmid, B.; Loreau, M.; Forrester, D.I.; Fei, S.; Zhu, J.; Tang, Z.; Zhu, J.; Hong, P.; Ji, C.; et al. Multispecies forest plantations outyield monocultures across a broad range of conditions. *Science* **2022**, *376*, 865–868. [CrossRef]
155. Warner, E.; Cook-Patton, S.C.; Lewis, O.T.; Brown, N.; Koricheva, J.; Eisenhauer, N.; Ferlian, O.; Gravel, D.; Hall, J.S.; Jactel, H.; et al. Young mixed planted forests store more carbon than monocultures—A meta-analysis. *Front. For. Glob. Chang.* **2023**, *6*, 1226514. [CrossRef]
156. Seddon, N. Harnessing the potential of nature-based solutions for mitigating and adapting to climate change. *Science* **2022**, *376*, 1410–1416. [CrossRef]

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Heritage Resilience and Identity: Lesson from Trabocchi Coast about Climate Change Adaptation Strategies

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Abstract: Climate change and land use are major drivers of environmental and socioeconomic transformations in landscapes and in coastal areas. The objective of this study was to present an interdisciplinary and participatory research methodology for analysing the evolutionary process of a coastal case study, the Trabocchi Coast in the Abruzzo Region (Italy), from multiple perspectives, including climate change, technological history, conservation protocols, and social function. The goal was to assess the resilience of these coastal structures, i.e., their ability to cope and adapt to changes while maintaining their identity and recognition. The adopted approach combined qualitative and quantitative data from the meteorological analyses, literature review, and field investigations involving a participatory workshop, from which a significant portion of the analysed results presented here emerged. The results indicate that the Trabocchi Coast has undergone significant changes in recent decades, posing a serious threat to cultural heritage due to climate change (sea-level rise, coastal erosion, storms, flooding and salinisation), changes in use and mass tourism. However, these changes have also presented challenges and opportunities for coastal development, stimulating diverse resilient responses from local communities, ranging from resistance to innovation. The paper discusses the factors that may make the Trabocchi Coast a model of resilience considering these changes. This is supported by the role of local institutions as guarantors of the cultural heritage value of the trabocchi in that specific landscape context, as evidenced by the approval of the "Costa dei Trabocchi Special Territorial Project" by the Abruzzo Region in 2023.

Keywords: climate change; trabocchi; intangible cultural heritage; coastal areas; resilience; coastal management; adaptive strategies; heritage uses

1. Introduction

The Italian coast of the Adriatic Sea is characterised by the presence of "trabocchi," ancient wooden "fishing machines" [1,2], which are relevant examples of the vernacular architecture in this coastal area.

This study focuses on a particular region, characterised by considerable environmental, historical, and cultural value, marked by significant open debates on different hot topics, and marred by the presence of landslide phenomena across the territory.

The evidence emerging from the mapping, analysis, and research phases has revealed how the course of events has defined the evolutionary developments that are sometimes

notable and sometimes less invasive but, in any case, nonetheless incisive in defining the territorial physiognomy. Therefore, it seems clear how the participatory phase serves as the glue between the analytical phase and the practical feedback, enabling motivation, justification, and understanding of the dynamics at work.

The stretch of coastline in the Abruzzo Region, from the municipality of Ortona to Vasto, in the province of Chieti, is known as the Trabocchi Coast, with 31 still standing today [2], serving as symbols of regional local identity and heritage (Figure 1).

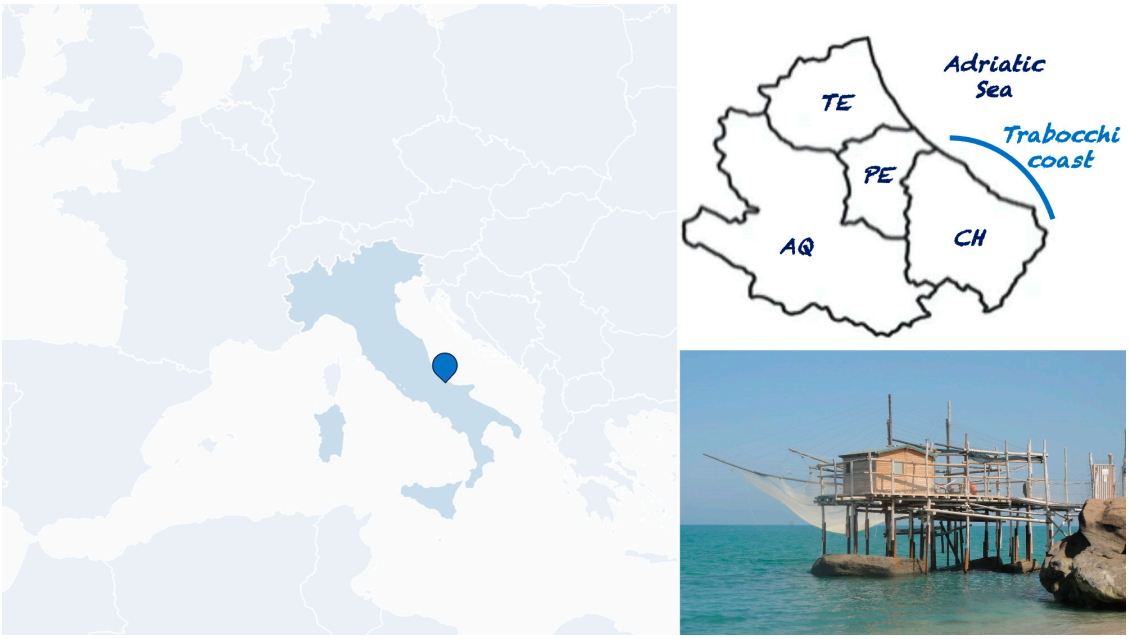


Figure 1. The five province of Abruzzo Region, Italy: TE, Teramo; PE, Pescara; CH, Chieti; AQ, L'Aquila) with highlighted the Trabocchi Coast along the coastline in province of Chieti and the Trabocco Punta Le Morge, Torino di Sangro (map by Alessandra Mascitelli and photo by Luisa Irazú López Campos).

Most trabocchi are privately owned, and only a third are subject to the constraints established by current national and regional protection laws [3] (p. 4). It is within the context of this coast and this specific vernacular architecture that our research is focused and must be framed in the dynamic context of what is happening in the Mediterranean basin.

The effect of climate change, for which the temperature appears to be a clear indicator, on heritage can be easily identified by the analysis of extreme weather-related consequences. The significant increase in extreme climate events, their intensity, and the related effects on the landscape and cultural heritage has been an emerging theme in the existing literature [3–6].

Specifically, regarding the Abruzzo Coast, it was observed that being affected for most of the year by the clear contrast between the tropical air masses and those of polar origin allows for the transit of unstable weather [3,7]. Studies have shown that the main cause of the risk of coastal erosion is storm surges. Their potential increase in the Adriatic Sea must be seen in relation to the increase in wind speed; in particular, it was tested how future storm events can be generated by increasing the wind intensity of the meteorological model [8].

In a previous study, the authors analysed the case of the Trabocco Turchino [3], recognised by the population as an identity element of the Abruzzo coastal area. This trabocco, which collapsed due to a strong sea storm in July 2014 and previously in 2003, has since undergone the recovery interventions and been destinated to a new function for cultural and tourist purposes [1,3,9,10].

The historical analysis of the trabocchi serves as a valid case study for understanding the institutional process of recognising cultural heritage and the social motivations behind it. This understanding underscores the need for conservation and the importance of studying the causes that challenge it, such as climate change and, as in this specific case, the resulting extreme weather events that increasingly affect the Adriatic Coast. Conservation strategies aimed at transmitting our cultural heritage to future generations must consider the value that the property has for its population and the function it serves. Such recognition and function in the present will enable it to survive the passage of time and be projected into the future. Hence, there is the need to monitor changes in the environment and plan concrete actions aimed at the conservation of cultural heritage by adapting it to these environmental stresses in order to make it resilient [3].

In this study, after the literature review on the historical, socio-economic, and conservative aspects in Section 3, we provide a climatic characterisation of the Abruzzo Region in Section 4, specifically for the province of Chieti, focusing on temperature trends that highlight ongoing changes and their likely consequences in terms of extreme events. This analysis scientifically supports the population's perception of climate change, as evident from the participatory workshop conducted with citizens in San Vito Chietino discussed in Sections 5 and 6, and further commented on in Section 7 prior to reaching the conclusion in Section 8.

2. Research Aim and Methodology

The main objective of this study was to present a methodological approach for analysing the Trabocchi Coast from various research angles, especially in light of the challenges presented by climate change, land use changes, and resilience capacity. We explored the significant historical, climatological, and social factors of the region to assess how climate change, resilience, and land use alterations have impacted the preservation of its cultural heritage. The research aimed to address the following key questions:

- How has the Trabocchi Coast changed over time in response to environmental factors and climate change?
- What are the current and future threats and opportunities for the conservation of trabocchi in relation to social and economic factors?
- How do local communities perceive and value the Trabocchi Coast and its heritage?
- In what ways can trabocchi serve as a model of resilience for other cultural assets?

To address these questions, we proposed an interdisciplinary and participatory research methodology [11] that involved researchers from different disciplines and actors from different sectors. The research team was composed of experts in meteoclimatology, communication, history of art, conservation science, cultural history, cultural mediation, and environmental sciences, who collaborated to collect and analyse data from diverse sources and perspectives.

The strategy and group work method involved contributions from various disciplines and specialties. The collaborative effort aimed to generate a proposal for addressing the impact of climate change on heritage elements, specifically focusing on trabocchi but remaining potentially applicable to any other cultural asset. The objective was to provide guidelines that could benefit decision-makers, local authorities, and the broader public.

By enhancing the understanding of heritage issues, the aim was to assist these stakeholders to make more informed and up-to-date decisions, including specific intervention proposals for conservation efforts. The research group's working methodology intended to offer a precise, comprehensive, and detailed perspective, achieved through the multidisciplinary composition of its members and, importantly, by considering the perspectives of various involved actors/actants [11]. This inclusive approach allowed for the analysis of a broader range of valuable elements, including social perception.

The proposed research methodology was grounded on the following principles:

- Interdisciplinarity: The research integrated the knowledge, expertise, and methodologies of diverse researchers from different disciplines. This approach aimed to offer a comprehensive and holistic understanding of the focal issue, in this instance, the Trabocchi Coast and its dynamics. The research team collaborated collectively to delineate the case study, set research objectives, design the research plan, determine data collection and analysis methods, and identify effective means of disseminating the results.
- Participatory Methodology: The research engaged different actors in the co-production of knowledge and information gathering, and in the elaboration and definition of key points related to cultural and social policy. This approach aimed to enhance the relevance, timeliness, and validity of the obtained results [12]. Stakeholders were involved from the beginning, consulted, and actively invited to participate through the implementation of a horizontal participatory workshop, a crucial component of the research process. They contributed essential elements, including identifying strategic lines, formulating research questions, and validating and assessing the research findings. In terms of transparency and ethics in data handling, participants were promptly informed of the workshop's objectives and had agreed that the information provided by them would be used by the research group for analysis and to enrich the research results that underlie this publication. Likewise, they agreed to the use of photographic images being taken during the group activities for the purpose of disseminating the work accomplished.
- Horizontal Approach: In addressing any issue, it was recognised that all the involved actors held equal importance, contributing key elements for a comprehensive understanding of the case study. While not everyone is the same or establishes identical dynamics or connections, everyone holds equal value when delving into any issue in depth. The horizontal approach was fundamental in this research proposal, acknowledging that each actor is essential [13].

The expected benefits of this research concerning trabocchi as heritage elements include:

- Generating a detailed and comprehensive understanding of the Trabocchi Coast and its resilience, considering the complexity and diversity of environmental, historical, cultural, touristic, social, and economic factors.
- Fostering, facilitating, and promoting dialogue and collaboration among researchers and actors involved, enriching reflection and knowledge generation, valuable for identifying objectives and proposing concrete solutions for the Trabocchi Coast.
- Enabling the research group to understand the perception of various actors involved in the trabocchi issue regarding the meaning of heritage. It is crucial to comprehend the heritage value attributed to trabocchi, its evolution, and how it has been affected or modified over time.
- Providing stakeholders with a comprehensive perspective on the issue, empowering them to participate in an informed and responsible manner in decision-making and propose concrete actions for the conservation and sustainable development of the Trabocchi Coast.

3. The Abruzzo Trabocchi: Fishing Machines between Tradition, Oblivion, Rehabilitation, and Reuse

3.1. Literature Review

In recent years, an increase in the extensive scientific literature on the topic of the Trabocchi Coast has proliferated in parallel with the enormous increase in tourism and media attention.

This section delves into the region's historical background, providing a basis to understand its current heritage landscape. Looking back on the recent history of this characteristic vernacular cultural heritage, up until the 1970s, maintenance work on these fishing machines was carried out by the fishermen themselves who worked there, without altering

the system's organisation. The railway, built in 1863-1864, which ran along the coast from Ortona to Vasto, was integrated into the natural and agricultural landscape and preserved this portion of the coast from building development. This 26 km coastline is at high hydrogeological risk due to its particularly vulnerable cliffs [3,14].

The sudden socio-economic growth has caused negative effects in this area. The choice of technologies and building materials foreign to the local culture, the progressive shift away from traditional knowledge and technologies, and the rise in mass tourism did not take into account the environmental consequences for this fragile area.

During this period (the 1970s and 1980s) of rapid growth and transformation, which saw people looking for more lucrative jobs, the trabocchi were mostly abandoned. However, it should be underlined that this phenomenon of under-utilisation began at the end of the Second World War [15] (p. 334).

Since the early 1990s, the interest of the institutions responsible for the full protection of these traditional fishing machines has grown [3] (pp. 3–4). Starting from 1994, specific regional laws have proposed measures for the recovery and enhancement of this so-called "spontaneous architecture", as representative instances of the construction practice of the *genius loci* [1] (pp. 246–247). These laws have initiated funding supported by the creation of a specific guide for the restoration and maintenance of these fishing machines. The topic regarding the construction of new trabocchi with adequate technologies and materials has also been addressed [9].

The decommissioning of the railway (Figure 2), which occurred in 2005 [14] (pp. 323–335), triggered a broad debate on the future of the coast and led, at the same time, to the rediscovery of the trabocchi. In this perspective, the "Theatine Coast Park" ("Theatine" means the stretch of coastline in the province of Chieti), promoted since 1997, was established to protect the areas of the coast freed from the railway.



(**a**) (**b**)

Figure 2. (**a**) Decommissioned railway station in the Municipality of San Vito Chietino; (**b**) Decommissioned railway stretch along the coast of San Vito Chietino near Trabocco Turchino (photos by Fernanda Prestileo).

From a legislative and planning perspective, an approach aimed at achieving integrated conservation has been outlined, based on the principles established by the "Amsterdam Declaration" [16]. This is in order to protect the entire landscape context of the Trabocchi Coast and prevent the improper use of the territory from erasing its cultural identity in favour of a standardised landscape, indifferent to coastal problems and environmental vulnerability.

Tourism impacts both, physical development and image, and could play a significant role in causing strong anthropic pressure [1]. This stretch of coast is, in some places, still free from tourist interventions but threatened—now that it is no longer protected by the presence of railway—by the pressure of a new real estate expansion which, in part, has already begun.

From the study and rediscovery of the trabocchi, the knowledge useful for activating adequate actions to achieve sustainable use of coastal environmental resources has continued to be developed, such as defining guidelines for the creation of sustainable bathing facilities [14] (pp. 30–33). The need to respond quickly to growing tourist demand has led to the defining of a new eco-systemic approach, falling within the new scope of "environmental planning". In this context, climate change is closely linked to the concept of resilience which is configured as the type of attitude to adopt [14] (pp. 13–16).

In January 2023, the Department of Territory and Environment of the Abruzzo Region adopted the Special Territorial Project (STP) of the Trabocchi Coast entitled "Enhancement and Requalification of the Theatine Coast". The project, which is configured as a complex project of a wide area, is in response to the priority objective of enhancing the coastal area of the Theatine Coast to guarantee the quality of its development and its territorial transformations, while respecting the environmental, historical, and landscape values present [10]. The STP includes the southern part of the Abruzzo Coast, which is scarcely urbanised and partly intact, from the municipalities between Ortona and Vasto.

In accordance with the design vision indicated by Forlani [14], the purpose is to achieve a new idea of territory that takes both the protection of the environment and its strong tourist vocation into account, promoting a form of experiential tourism (slow crossing of the landscape). The STP intends to structure a widespread tourist system of excellence that finds its self-generating strength in the protection and safeguarding of local identities and authenticity (environmental, landscape, historical, architectural, and artistic).

Among the numerous objectives mentioned, the STP is aimed at facilitating interventions around the "Green Corridor of the Province of Chieti" [17], starting from the use and enjoyability of the same infrastructure together with the recovery and unitary repurposing of disused railway stations. In fact, the Green Corridor consists of all the disused railway areas of the coastal line between Ortona and Vasto Marina acquired by the Province of Chieti together with the former railway stations. It also includes the "Green Road of the Province of Chieti", a cycling and walking route as non-motorised slow infrastructure is irreplaceable for the enhancement of the environmental resources of the coastal area and for the valorisation of public and private property, as well as for a new way of enjoying the coast [10].

The STP also provides for active conservation to maintain the constituent values and morphologies of the territory, also taking into account the architectural typologies, as well as the techniques and traditional building materials. Among the various actions planned, there is also the promotion of environmental recovery activities aimed, in particular, at maintaining the safety of areas characterised by potential geological and hydrogeological hazards, as well as the enhancement of the environmental ecosystem and of the connotative features of the coastal landscape.

The intervention criteria and guidelines of the STP must be consistent with the indications deriving from the Guidelines and the Climate Profile of the Climate Change Adaptation Plan of the Abruzzo Region (PACC) and from the Analysis of the possible costs of Climate Change. This analysis must consider different risk scenarios of sea level rise (SLR) or increased flood risk and on the estimate of the monetary value of the areas exposed to a possible risk of soil loss in the scenarios considered in the study (APAT and CMCC) [10,18].

3.2. Recovering Trabocchi: Some Considerations

Regarding the conservation of this type of artefacts, some problematic aspects have been highlighted which reveal the complexity of the issue, since it involves a theoretical and

planning reflection pertinent to the sphere of both intangible and tangible cultural heritage. The dual nature of these artefacts must be considered, as these are structures suspended between land and sea, destined not to last over time [2], and which have undergone periodic renovations and replacements starting from the 19th century, even if they are attested in the 17th century [19]. Currently the trabocchi in Abruzzo, which have remained intact to our days, were built over a period time ranging from the 1880s to 1930s [20] (pp. 38–49). According to Serafini, "Being machines used traditionally for fishing, and therefore as productive buildings to all effects, trabocchi may be considered a particular articulation of what is termed 'industrial archaeology'" [2] (p. 658). These structures, which appear fragile in appearance, are structures constituted of very specific elements that make up the system, including the gangway, fishing plate, stabilising grid, fishing device, and functional equipment (Figures 3 and 4). The evolutionary process characterising these artefacts took place as a function of changes due to the transfer of technology (first and foremost, the construction of the railway) and to changes due to the change in use, fundamentally, but not exclusively, from fishing to the catering service of the seaside tourism system. In the first case, mutations mainly concerned the technical, constructive apparatus, in the second case, they concerned the morphological dimensional system for reasons related to the possible extended use and therefore to the necessary safety [9].



Figure 3. Trabocco La Rosa dei Venti-Canale-Trabocchi Coast (photo by Luisa Irazú López Campos).

It follows that, concerning these artefacts, we cannot analyse their codified conservation history according to the criteria of philological restoration, which is intended as a complex of investigations and actions that aim to bring the artifact back to its original form, freeing it from subsequent additions or alterations. In this case, traditional knowledge and construction techniques have come into play which, as emerged from the literature [15] (pp. 328–337), have been passed down orally based on the function of the trabocchi (fishing), on the adaptability of the materials with respect to the landscape context and, lastly, on the structure which had to adapt to the conformation of the coast (sandy or rocky) [2] (p. 650). The use of tradition and the recovery of ancient knowledge are profoundly immaterial aspects that must be documented. To this end, the STP project promotes the recovery, maintenance, and valorisation of the trabocchi, guaranteeing the appropriateness of these management actions over time, and avoiding their historical, cultural, and landscape debasement [10]. It has been established that the trabocchi must be recovered by means of the techniques appropriate to their restoration and renovation. The trabocchi can also be

reconstructed where ancient pre-existences can be found and contribute to the equipment of the coastal selvedge, with uses related to small-scale fishing and educational activities aimed at the knowledge of the marine environment, as below explained.

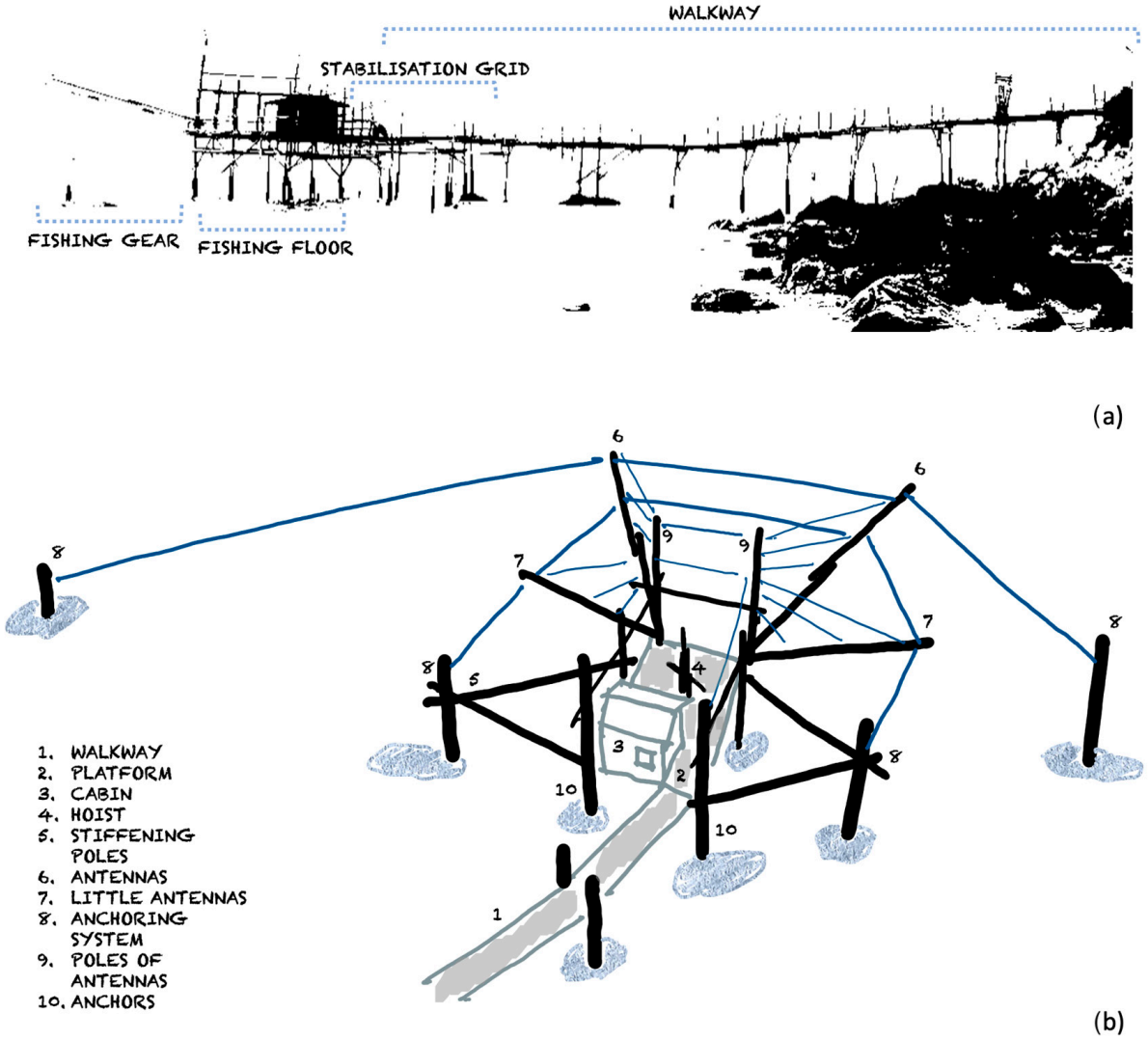


Figure 4. (**a**) Trabocco operational features (**b**) Trabocco structural elements.

Indeed, the trabocchi, as identity elements, must be preserved and maintained in their typological, constructive structure. Therefore, the constituent materials, the composition and volumes must remain unchanged and consistent with the original image of the artefacts. Projects supported by joint actions between the municipalities of the Trabocchi Coast, the Province of Chieti, the "Soprintendenza Archeologica Belle Arti e Paesaggio" (Superintendency of Archaeology, Fine Arts, and Landscape), and Abruzzo Region in continuity with the good practices initiated over time for the same purposes of urban and territorial regeneration of the territory of reference must be carried out and implemented. This is the case of the reconstruction of the Trabocco Turchino (Figure 5), which is the only one of public property, destroyed in 2003 and in 2014 by two different sea storms [1,3,9,10], which has since been used by local associations for cultural and social purposes.

Following this exploration of the historical context that shaped the region, we will now examine how climatic conditions have impacted its evolution and development, and the preservation of its cultural heritage elements over time.

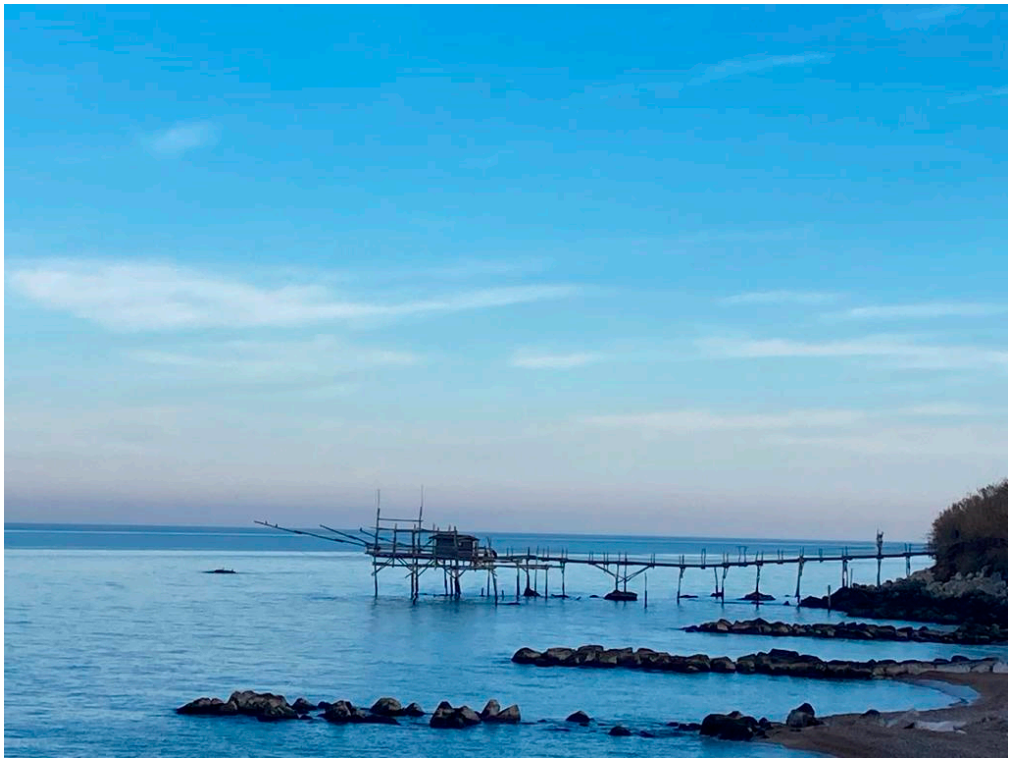


Figure 5. Trabocco Turchino–San Vito Chietino–Trabocchi Coast (photo by A. Mascitelli).

4. Meteorological–Climatic Characterisation of Abruzzo Region

The climate of the Trabocchi Coast significantly affects its environmental and cultural heritage. Analysing climatic patterns and their historical effects is key to evaluating the future resilience of the region's cultural heritage. In reference to the dual emergency situation experienced by Trabocco Turchino [1,3,9,10], the transition to the research segment analysing the climatic conditions in the region is now undertaken. This exploration aims to elucidate the factors contributing to the area's susceptibility to risks arising from climate change.

In this context, the need to understand the coast characteristics in order to comprehend the weather-related phenomena features and be able to impact the stability and the conservation of the studied area becomes clear. In the analysis of the stability conditions of the slopes connecting directly with the line of coast of the Adriatic Sea [21–23], in the stretch between Pesaro and Vasto, there is a cliff for large stretches raised up to approximately 200 m above sea level. Landslides, often large, are already known and described starting from the 19th century [24], have involved the area periodically and on several occasions. From Torre Mucchia to Punta Penna, near the port of Vasto, the coast is high with the presence of short pebble and sandy beaches in the large inlets which the crag appears to be structured. Only at the mouth of the Sangro river the continuity of the high coast is interrupted by a wide sandy coast. South of Punta Penna, up to beyond the port of Termoli, there is a succession of cliff sections and sandy beach sections. The Adriatic coastal strip and its immediate hinterland are characterised by outcrops of Quaternary formations of coastal and deltaic facies, covering the marine silty clays of the Plio–Pleistocene age. The coast is currently subject to intense erosive activity due to the lack of sediments carried by rivers (along which there has been a strong increase in activity in recent years mining) and from the sea (where many cliffs are now protected with shore walls or breakwaters). A comparative analysis of the historical, geometric and dynamic data of some coastal landslides in the Adriatic regions allows us to recognise some substantial similarities and hypothesise the existence of a common failure mechanism. The mechanism is very simple—the collapsed material apparently advances the front beach; however, this local growth of

the coast is short-lived, as the materials' landslides are easily mobilised by wave motion and redistributed along the coast. Unique evidence of the landslide event is given by the larger boulders remaining in the lower areas of backdrops [25,26].

Starting from this basis, the aim of this section was to describe the climate change in the Abruzzo Region and its influence on the whole Trabocchi Coast, a 26 km stretch of the Adriatic Coast characterised by these ancient wooden fishing machines. We analysed the temperature trends since 1930, using the data measured by the network of the former Regional Hydrographic Institute and currently managed by the Functional Centre of the Abruzzo Region. We also used the ERA5 dataset [27,28], a global reanalysis of atmospheric, land, and ocean observations, to compare our results on a larger spatial and temporal scale. We found that the temperature increased coherently with what happened in the northern hemisphere, and that the increase was more pronounced in spring and summer, especially in the most recent period (1980–2015). We also found that some areas have local microclimates that induce variations in temperature above the regional average. These results, combined with an analysis of wind gust and convective precipitation patterns, painted a clear picture of the environmental stresses to which the area is exposed, and showed significant evidence of impact on the territory.

4.1. Data and Methods

We used the historical temperature series measured by the network of the former Regional Hydrographic Institute and currently managed by the Functional Centre of the Abruzzo Region. The network consists of 22 stations with the most complete data record since 1930, as many stations were recently activated while others were decommissioned over the years. The stations are located at different altitudes and covermost of the regional territory. The data include the maximum, minimum, and daily mean temperatures.

Before using the historical temperature series, we performed a data homogenisation and quality control process to consider any variations in the data attributable to external factors, such as movement of the station, change of measurement system and human error [7]. We also compared our data with those of the nearby stations and with the ERA5 dataset to ensure consistency and reliability.

The ERA5 dataset is a global reanalysis of atmospheric, land and ocean observations, produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). It provides hourly data on many variables, such as temperature, precipitation, wind, humidity, pressure, and radiation, at a spatial resolution of about 31 km. The ERA5 dataset covers the period from 1940 to the present and is updated monthly. We used the ERA5 dataset to compare our results on a larger spatial and temporal scale, and to validate our data and methods.

We analysed the temperature trends for each station and for the regional average, considering maximum, minimum, and daily mean temperatures. We also performed seasonal analyses, dividing the year into four seasons as follows: winter (December–January–February), spring (March–April–May), summer (June–July–August), and autumn (September–October–November). We calculated the trends by linear regression model (least-squares best-fit) in different temporal intervals (1930–1979, 1950–2015, 1980–2015) to find the slopes as function of the period.

4.2. Results and Discussion

The analysis of the temperature trends in the Abruzzo Region shows a clear and consistent increase in all stations, seasons, and time intervals, in line with the global and regional warming observed in the northern hemisphere. The increase is more marked in the most recent period (1980–2015), and in spring and summer.

The annual regional mean temperatures, considering the average on the observation stations available in the Abruzzo Region, show an increase in the daily mean temperature, maximum and minimum, with a greater rate starting from 1980. The daily mean temperature shows an increasing trend in the period of 1930–1979, equal to 0.13 °C every 10 years,

while considering the period of 1950–2015, the increase is equal to 0.42 °C per decade, an increase which becomes even more pronounced (0.60 °C per decade) considering the period of 1980–2015. While there is a positive trend at the regional level in terms of the time span (1980–2015), there are areas, such as Chieti (Figure 6) and Pescara, where local microclimates induce variations in positive rates of temperature increase above the regional average. Moreover, considering the period of 1950–2015, Lanciano (about 10 km from the coast) shows a significantly higher increase trend (0.44°/decade) than the regional average.

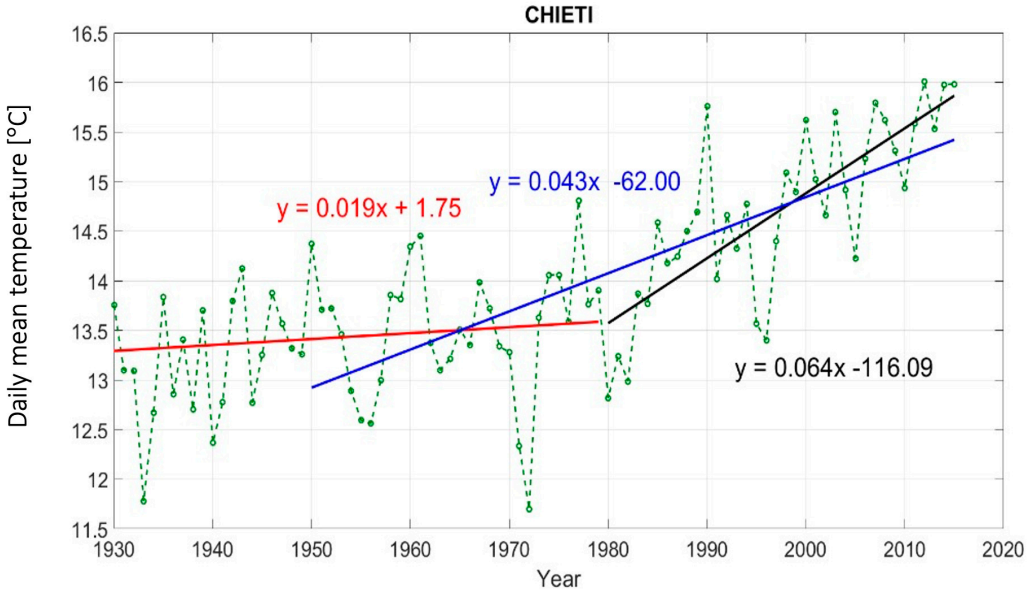


Figure 6. Daily mean temperature through the years over Chieti area.

Considering the maximum temperatures, averaged over all the measuring stations available in Abruzzo, in the period of 1930–1979, the change is slight and equal to 0.10 °C per decade; whereas in the period 1950–2015 the temperature increase is equal to 0.63 °C per decade (0.21 °C greater than the increase in mean daily temperature compared to the same period); with Pescara and Lanciano showing a trend of 0.65°/decade and 0.64°/decade respectively. Moreover, in the time interval of 1980–2015, the increase is equal to 0.78 °C per decade, therefore 0.18 °C higher than the increase in the mean daily temperature in the same period. Locally, Pescara showed much higher variation (0.92 °C/decade).

The minimum temperatures, averaged over all the measuring stations available in Abruzzo, show in the period of 1930–1979, a change equal to 0.18 °C per decade; in the period of 1950–2015, the temperature increase is 0.22 °C per decade, and in the time interval of 1980–2015, the increase is equal to 0.42 °C per decade. Locally, Chieti shows higher variation with 0.24 °C/decade and 0.47 °C/decade for the periods of 1950–2015 and 1980–2015, respectively.

Seasonal analyses, always considering the daily mean temperature and the average over all the Abruzzo measuring stations, show that the temperature increase over the period 1950–2015 is more marked in spring and summer with a rate of 0.46 °C per decade, while in autumn and winter a variation between 0.39 °C and 0.37 °C per decade is observed. On the contrary, in the most recent time interval (1980–2015), there is no clear distinction between spring–summer and autumn–winter; however, more marked differences are observed in the individual seasons as follows: in spring, there is the greatest increase (0.75 °C per decade), while in autumn, there is the smallest (0.42 °C per decade). Finally, in summer and winter, the increase is 0.69 and 0.51 °C per decade, respectively.

The comparison of our results with the ERA5 dataset shows good agreement and consistency, both in terms of magnitude and direction of the trends. The ERA5 dataset also allows us to extend our analysis to a larger spatial and temporal scale and to see how the temperature trends in the Abruzzo Region are related to the global and regional climate

change. We find that the temperature trends in the Abruzzo Region are similar to those observed in the Mediterranean basin and in Southern Europe, which are among the most vulnerable and exposed areas to the climate change impacts [7].

The results, combined with an analysis of wind gust and convective precipitation patterns [3] (p. 6), paint a clear picture of the environmental stresses to which the area is exposed, showing significant evidence of impact on the territory [3,29].

5. The Importance of the Social Factor in Heritage Conservation: A Proposal for Addressing It

5.1. The Institutional Recognition of the Role of the Local Community in Heritage Conservation

Having conducted an extensive multi-temporal examination of the historical and climatological dimensions of the Trabocchi Coast in the Abruzzo Region, we now complement our approach by focusing on the social factor—the populace and its role in the perception, appreciation, and preservation of local heritage. Beyond the environmental, scenic, historical, and monumental assets spanning the entire Trabocchi Coast, the Special Territorial Project 2023 (STP) [10] regards the inhabitants as the genuine wealth of the region. They represent intrinsic components of authentic and identity-shaping local communities, highlighting the intimate connection between residents and the territory. For this research, as well as for the proposal of the STP 2023, considering the social aspect is one of the main pillars of our approach. If we do not consider the population as a fundamental actor in heritage conservation, the work becomes somewhat senseless. The current significance of heritage conservation lies in acknowledging the importance and use that heritage elements can and should have [3], especially in improving the quality of life for those who use and enjoy them, by serving as reinforcing elements of their identity and self-esteem, and as a tool for better self-assessment as individuals and as a collective. Despite appearing logical and almost intuitive, recognition of the role of citizens in heritage matters has not always been present or valued, even by organisations such as UNESCO, a recognised advocate for heritage-related concerns.

An example of this is that, in 2002, on the 30th anniversary of the UNESCO Convention Concerning the Protection of the World Cultural and Natural Heritage, this institution, through the Budapest Declaration, established as key strategic objectives for heritage "the 4 Cs" [30], Credibility, Conservation, Capacity Building, and Communication. It was not until three years later, in the 2007 World Heritage Committee, that a fifth "C" was added, Community [31], recognising the vital involvement of the local community in safeguarding and protecting its heritage, 33 years after the Convention's origin. Therefore, our proposal includes considering the population as one of the relevant actors in institutional decision-making, so that, drawing from their experience as users of assets considered heritage, we enrich the experts' perspective, making it a fundamental complementary element when designing and implementing regulatory strategies, such as the STP.

5.2. A Participatory Horizontal Tool That Acts as a Social Thermometer for Local Heritage Perception

Following the institutional recognition of the significant role of the local population in heritage matters, the challenge became how to address this citizen-driven work. Our focus is on implementing strategies that include them, take them into account, consider their input and, above all, allow them to have influence in the decision-making process. This is where a crucial aspect of our research proposal lies, in the design of a participatory tool used to acquire knowledge, collect data, and gather opinions from local actors involved. Thus, the conceptualisation, design, organisation, execution, and analysis of a horizontal participatory workshop [32] conducted in November 2023 in San Vito Chietino, one of the municipalities of the Trabocchi coastline. The objective of this tool was to engage the local community in a dialogue about their perception of the past, present, and future of the Trabocchi Coast (Figure 7). This encompassed their understanding of the concept of heritage, the elements they consider as part of their heritage, and the challenges and opportunities they identify in the region.



Figure 7. Trabocco Punta Fornace, San Vito Marina—Trabocchi Coast (photo by Luisa Irazú López Campos).

Thirty participants voluntarily attended the workshop, having been directly invited by the Municipality of San Vito Chietino, which provided us with a working space in its facilities, and by residents who helped spread the word about the activity. Participants came from various locations in the Abruzzo Region and other parts of Italy. They represented diverse groups, including local authorities, cultural associations, environmental groups, and citizens of all ages, ranging from a 5-year-old child to families, seniors, young people, couples, and individuals attending alone. Each attendee actively participated at some point during the workshop, fostering a sense that their voice was equally relevant, useful, and important throughout.

In methodological terms, it is important to mention that the workshop was conducted through an open call. This was announced by the municipality and through direct, word-of-mouth invitations among friends and acquaintances. Citizens of all ages, including children and young people living on the Abruzzese coast, were invited to share their reflections with other citizens about the cultural elements they considered most relevant in their environment and their perceptions of how these elements should be used and preserved. There was no pre-selection of participants or formal registration. The workshop engaged with the group that formed at the time. Attending to the group that formed, regardless of its composition, was part of the horizontal methodological strategy employed, where each participant's contributions, opinions, reflections, and proposals were considered equally important in terms of their validity [32]. The workshop comprised two main segments, a plenary session and a group participatory work session. During the plenary session (Figure 8a), the scientific committee introduced the research project and its objectives, emphasising to attendees the crucial role their contributions would play. In this regard, attendees were asked for permission to use the data generated during the workshop for academic and scientific purposes, to which there was unanimous consent. During the working session (Figure 8b), participants collaborated in groups, focusing on specific topics related to the themes of the research. The objective was to facilitate the sharing and exchange of views and experiences concerning heritage in the Trabocchi Coast. This process yielded updated and first-hand information about the local inhabitants' perception of their

regional identity and heritage references. The workshop presented a valuable opportunity to collect qualitative data and ideas.



Figure 8. Horizontal participatory workshop "Conservare il mio Patrimonio" (Preserve my heritage), November 2023, San Vito Chietino—Trabocchi Coast; (**a**) plenary session (**b**) group participatory work session (photos by Fernanda Prestileo).

It is essential to highlight that the participatory methodological tool designed for this exercise does not presuppose that the representativeness of findings should be measured by the number of participants involved. Given that it produces qualitative rather than quantitative data and is grounded in horizontal methods of work, each contribution bears inherent value. Each actor is unique, forming distinct connections and dynamics with the case study in question [11]. No single contribution carries greater significance than another, and all should be regarded equally during the analysis of results [32].

6. Results Achieved through the Utilisation of the Social Factor (Citizen Participation) as a Key Element of Our Research

Before kicking off the discussion, some of the key issues, findings, and perspectives that emerged from the horizontal participatory workshop, which are relevant to the research addressed in this study, are as follows:

- Concerns among residents regarding challenges stemming from mass tourism and urbanisation, which have affected the Trabocchi Coast in recent decades. These challenges have led to the erosion of the "human dimension" and the original identity of

small localities, coupled with inadequate services to address hygiene, accommodation, and transportation requirements.

- The imminent change in the use of trabocchi, transitioning from traditional fishing machines to trendy restaurants, raising concerns about the lack of promotion of their historical and functional roots, as well as their significance for the region's identity.
- Among participants, diverse perspectives emerged, with some viewing trabocchi as a commercial brand imposed by regional authorities, while others perceive them as symbols of the territory and sources of income.
- The argument that heritage conservation loses its essence when it fails to contribute to the well-being of its "emotional owners", the local community.
- The perception of trabocchi as cultural heritage elements that have survived and adapted to environmental and social changes over time.
- The local community places a high value on the emotional and historical connection with trabocchi, leading some individuals to establish associations or cooperatives dedicated to their preservation and management.

There was a shared recognition of the importance of striking a balance between tourism and the preservation of the natural landscape, as well as the transmission of trabocchi stories and traditions to younger generations. Some attendees to the workshop mentioned that the value of the trabocchi is based on what they represent from a historical and past perspective, while others asserted that their value cannot solely depend on what they signified in a remote era but rather on what they signify for the population in the present. Thus, they highlighted that while preserving the authenticity and history behind heritage is important, it is also essential to understand that its value resides not only in its past but also in its meaning and utility in the present. Many participants agreed that it is imminent for the trabocchi to change their use, but they were very insistent that their originality be respected in the process, especially in terms of materials, emphasising what we have already mentioned about the Italian tradition of conserving and restoring heritage, where the replacement of original construction materials is not appreciated and should be avoided as much as possible. In this dilemma between accepting the change and evolution of trabocchi while simultaneously being concerned about their conservation, everyone agreed on the need to adapt to the necessary strategies to prevent their disappearance, as their value lies in the meaning they have for the region, and that is where their importance lies, in terms of heritage, not only material but also emotional, and therefore, immaterial.

Regarding climate change, workshop participants asserted that its effects on the Trabocchi Coast has manifested both long-term consequences and immediate phenomena. Residents have observed irregularities in seasons and cycles, along with land and sea warming, and assert that this has led to a decline in biodiversity. They attributed the decline in traditional fishing activity and the abandonment of trabocchi to a notion deeply ingrained in the collective imagination of the region (Figure 9). This notion asserts a scarcity of fish near the coast caused by climate change and overfishing, yet it lacks substantial scientific backing and evidence. This argument relies on the collective imagination and its beliefs or perceptions, raising an important question about our responsibility as researchers. How can we democratise knowledge, making it accessible to the population, to challenge unfounded ideas or prejudices that have endured due to an apparent lack of information? Addressing this challenge is crucial to preventing the population from forming inaccurate connections and communications regarding the issue at hand, in this specific case, the trabocchi.



(**a**) (**b**)

Figure 9. Trabocco Punta Le Morge (2013)—Torino di Sangro, Trabocchi Coast—tight mesh net known as "trabocchetto": (**a**) Fishing technique; (**b**) detail of "papalina", the blue fish caught (photos by Luisa Irazú López Campos).

7. Discussion

As a point of discussion, we will begin by emphasising that it is noteworthy to observe that the demand we recorded in the community is for no changes, neither in the original structure nor in the traditional use of the trabocchi, perhaps as a way of repeating a static institutional discourse about heritage, rather than reflecting on the possibility of assuming that heritage in general, and more specifically, the notion of it, has changed over time, leading from a static perspective focused on its conservation to a more dynamic approach that recognises the importance of change and adaptation [33]. We thus report that, at the beginning of the workshop, they opposed the change in use, arguing that heritage should be inviolable—a powerful and definitive term in its meaning. As the workshop progressed and certain questions were posed on this matter, the participants acknowledged that the idea of no change might stem from an Italian way of thinking about the conservation of cultural heritage. This approach values the original, the initial, the authentic, without deeply reflecting on how this static nature can lead to the disappearance of a heritage asset due to lack of relevance and use for current generations. We can say that this way of conceiving heritage, its conservation, and its management largely come from established heritage practices in Italy, specified in the Cesare Brandi's Theory of Restoration of 1963, which not only exists to this day but is regulated by Italian legislations [34–36].

This research clearly highlights the need for cultural heritage to adapt and evolve to ensure its conservation and relevance in today's society. In this regard, we can emphasize that some attendees to the workshop mentioned the value of trabocchi for what they represent from a historical and past perspective, while others asserted that their value cannot solely depend on what they signified in a remote era but rather on what they signify for the population in the present. Thus, they highlighted that while preserving the authenticity and history behind heritage is important, it is also essential to understand that its value resides not only in its past but also in its meaning and utility in the present. In this dilemma between accepting the change and evolution of trabocchi while simultaneously being concerned about their conservation, everyone agreed on the need to adapt to the necessary strategies to prevent their disappearance, as their value lies in the meaning they have for the region, and that this is where their importance lies, in terms of heritage, not only material but also emotional, and therefore, immaterial.

Considering the definitions of resilience, defined as a criterion for vulnerability computation of a site of cultural and natural interest in Europe [37–40], a flow chart has been included in order to obtain an overview of the topics considered and addressed as the object of this study (Figure 10, green text) and in the previous one [3] (Figure 11, orange text), as

well as the topics considered but not analysed for the purpose of this study reported in this paper (Figure 10, red text).

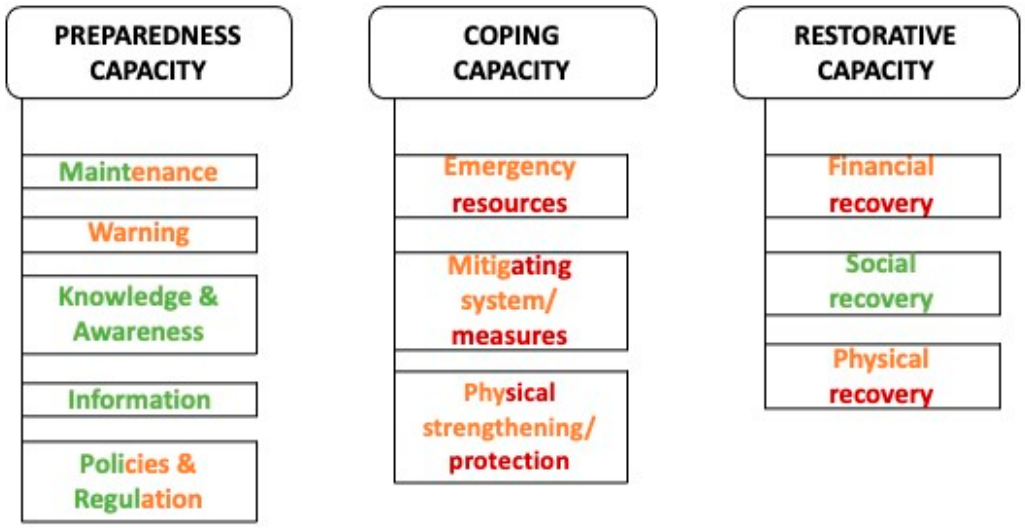
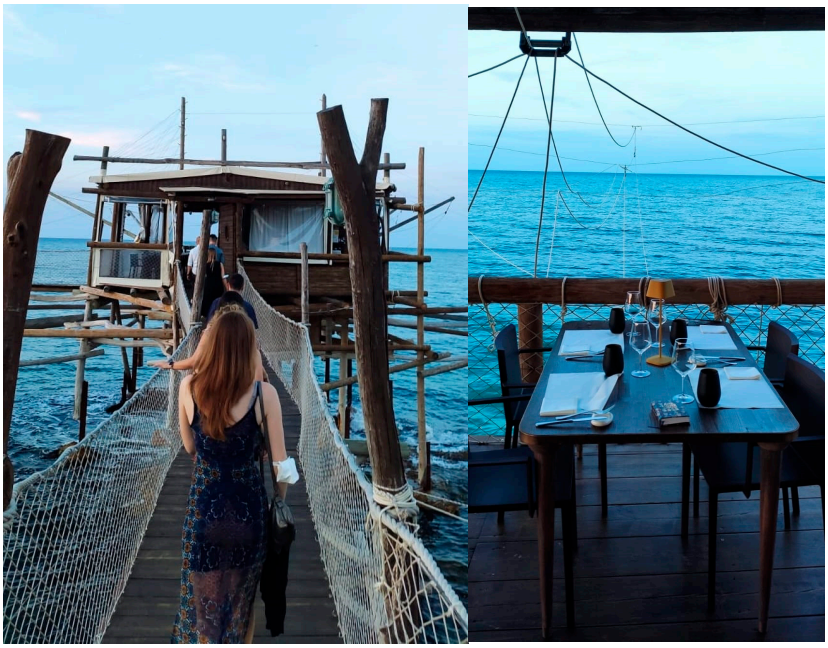


Figure 10. Flow chart of criteria, belonging to the definitions of resilience considered in our study based on vulnerability methodology defined by [38,40] in green text, topics considered and addressed as the object of this study; in orange text, topics addressed in our previous study [3]; in red text, topics considered but not analysed for the purpose of this study.



(**a**) (**b**)

Figure 11. Trabocco Mucchiola (2023)—Ortona, Trabocchi Coast—Current use of trabocchi as restaurants: (**a**) Restaurant customers entering the trabocco via the walkway; (**b**) detail of one of the tables in the restaurant (photos by Valentina Profeta).

Following collective reflection and analysis, workshop participants agreed that if the use as restaurants had not been assigned, several trabocchi on the Trabocchi Coast would probably have disappeared by now (Figure 11). Delving deeper into this, workshop participants engaged in a reflection on what heritage resilience means and how it is closely related to the use of cultural assets, and how heritage adapts to changes through various strategies. From this, we consider that the discussion should encompass the fact

that some heritage assets, such as the trabocchi, were not originally constructed with the intention of standing for a long time. Their persistence in time is decided once they acquire not only a utilitarian but also a heritage significance, at which point their management, use, and therefore conservation strategies become more complex. Thus, if these elements now considered heritage adapted to their change in perception [41,42], transitioning from utilitarian elements to becoming reference points for a social group, territory, and culture, we must be consistent and then provide them with the strategies and tools to adapt to the necessary changes to fulfil this role. It is a reality that they are no longer useful in terms of their fishing activity function, but rather in terms of the emotion, the identity [43,44], and the link they have acquired over time, which require them to remain standing longer than originally planned and intended. For this, they must be resilient and adapt to the new demands and realities of the context. Among these new realities is, as we have demonstrated throughout the research, climate change and its effects on the region, specifically those caused by rising temperatures, which can accelerate coastal erosion processes [45–47], affecting marine ecosystems [48,49] and influencing increasingly frequent and intense extreme weather [50,51] events, such as storms or floods [52–54]. Thus, the strategy that has naturally emerged in the region is to resort to changing use as a strategy for persistence and therefore as an element of resilience, which so far has proven to be the only valid and functional strategy to ensure, at least for now, the conservation and durability of the trabocchi over time, a time for which they were not programmed or envisioned at the time of their original construction.

In terms of climate change, we emphasise that from the participatory group reflection, several other specific situations resulting from this phenomenon in the region were identified, such as the consequences of the loss of the characteristics of the traditional seasons. In this regard, the participants asserted that the climate has undergone dramatic changes, as already reported in this document, compelling them to adopt resilient measures such as harvesting crops earlier, both in vineyards and olive groves. It is common in the Abruzzo Region for residents to have vineyards or olive groves, either as a business, part of cooperatives, or for personal or family consumption. Hence, several attendees at the workshop shared their sentiments regarding this new reality, stating that climate change has had a severe impact on the region, affecting aspects of its tangible and intangible heritage. An example of this is the impact on its rural culinary heritage. Consequently, they have had to implement drastic measures to avoid crop loss and adapt to the new timings. Now, strategies must change. The impact has been felt in daily life and has affected heritage-related activities, traditions, ways of living, and modes of social organisation. This highlights that, particularly in heritage-related matters, the impact of climate change is imminent. We can translate the results obtained throughout this research by affirming that resilience in heritage matters not only exists but must persist to guarantee its conservation. One resilience strategy for heritage, particularly concerning the trabocchi, is changing their use, a reality already evident on the Trabocchi Coast in the Abruzzo Region. With extreme conditions, constant temperature changes, ongoing climate variations, strong winds, and tide variations, decisions must be made regarding this reality both in the region and globally.

The patterns of the seasons, including their timing, temperatures, and rainfall, have undergone significant changes. It is not feasible to apply the same processes on the same dates as before, particularly in terms of harvests and fishing. The resilience of the population serves as a valuable resource for implementing new processes and strategies, thereby ensuring the preservation of know-how, knowledge, traditions, identity, and local heritage [55].

8. Conclusions and Future Perspectives

It is crucial to recognise that heritage is not a static element but a dynamic one, evolving in use and perception over time at both institutional and social levels. Our proposal therefore is to work towards recognising and differentiating what is inherent

in the institutional discourse and management of heritage from what emanates from the emotions and identity attachment of the local population, referred to as "social perception". Once this distinction is acknowledged, the proposal is to enhance and complement the institutional vision of heritage with that of the citizens, those who live and use heritage assets, thereby allowing us to have a comprehensive and contemporary understanding of the heritage values that are significant for the population and for the institutions and thus reach a consensus between both assessments in order to make better decisions regarding their management and conservation. The inclusion of the voice and perspective of the population can undoubtedly improve the legitimacy, and, above all, the effectiveness of the decisions taken by the institutions, the responsible parties, and the authorities in charge.

The workshop attendees agreed on the idea that heritage is a common good that "belongs" to them, a valuable concept when considering public and heritage policies by local and national institutions. Another element on which they agreed was that it is the state's responsibility to conserve heritage, arguing that institutions have the budget for it. It may seem contradictory to confidently declare ownership of heritage while simultaneously delegating its care to the state, but this highlights the lack of opportunity they often have to be actively involved in heritage initiatives. This method represents an opportunity to involve the population in projects related to the development of projects and strategies for the conservation of local heritage resources, making them active actors in the generation of ideas and initiatives that can endure over time, thanks to social commitment and agreement. It is a gap in institutional heritage management to involve them and thus capitalise on their sense of ownership to achieve successful and lasting projects.

In this regard, active participation of the local population in heritage-related decision-making is crucial to ensure its long-term preservation. Our participatory workshop in San Vito Chietino demonstrated how citizens are willing to contribute their knowledge, experiences, and perspectives to inform and enrich heritage conservation strategies. By engaging the community in this process, we not only strengthened their sense of belonging and local pride but also promoted a more inclusive and sustainable management of cultural heritage.

Based on the findings from the workshop, we see how the community is organising itself in response to temperature variations, creating new ways of doing things, new strategies as tools of resilience against the imminent changes caused by climate change. This speaks to how, in the present, we are not only the spokespersons and custodians of passing the heritage baton from one generation to the next, but we are also, as individuals and as a society, not only responsible for an existing and static heritage but also act as generators of heritage in the present. We are generators of strategies and new elements that complement the existing heritage, providing it with the necessary tools to endure and not disappear due to lack of relevance or meaning for those who use and enjoy it. Thus, the importance of inclusion in heritage is demonstrated, as is the importance of our proposal to include all stakeholders in the theme and work towards its conservation, as an act of democratisation of culture and the decisions made about it. We are thus generators of heritage in the present, impacting the path not just passing on the baton of its care and conservation; therefore, the argument for involving the population in the management and decision-making regarding its use and conservation is solidly supported.

Heritage, as an element of belonging and persistence, underscores the urgency of its resilience and adaptation to imminent changes in the territory, whether due to climate change, poor governmental decisions, wars, or other factors. In this sense, the analyses of impact of extreme meteorological events provides useful feedback to the question about the consequences of climate change, for which the temperature appears to be a clear indicator, on heritage and indicates how returning to a protection perspective favours both the reuse and conversion of structures compatibly with the characteristics of the area analysed. In this way, we can conclude that resilience in heritage is undoubtedly a powerful strategy to prevent its disappearance and that throughout this process, the population must always be involved. The issue of protecting the cultural heritage has its

basis in a previous work focused on the analysis of the intense weather that led to the collapse of the "Trabocco Turchino" structure. Its destruction in 2014 laid the theoretical and methodological foundations for defining the guidelines for intervention by safeguarding the "historical instance" recognised by local communities while ensuring its educational and promotional function. From what has emerged, it is evident how, throughout history, the social aspect has increasingly shown its key role in the preservation process. The common sense of citizens and consequently the bottom-up process of awareness, if properly introduced in decision making, can provide a clear support emphasising the importance of participatory planning even more in matters related to intangible cultural heritage. Local knowledge, traditional know-how, and those emerging over time are of enormous importance to consider when developing heritage conservation strategies in the face of the imminent effects of climate change, and when proposing new cultural and heritage policies. This is a thread of reflection that will be taken up in an interdisciplinary manner by this research group in future collaborative project endeavours.

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Data Availability Statement: Data are contained within the article.

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References

1. Forlani, M.C.; Borrone, M.; Radogna, D. Sustainable development and heritage: "Trabocchi" and the rules for building on the coast. *WIT Trans. Ecol. Environ.* **2010**, *128*, 245–257. [CrossRef]
2. Serafini, L.; Di Toro, N. Not just wood. The fishing machines of the central Adriatic. In *Roma, Capitale d'Italia 150 Anni Dopo. Preesistenze Architettoniche. Aree Archeologiche-Paesaggio*; Bellanca, C., Antonini Lanari, C., Eds.; Artemide: Rome, Italy, 2021; Volume 2, pp. 649–661.
3. Mascitelli, A.; Prestileo, F.; Stella, E.M.; Aruffo, E.; López Campos, L.I.; Federico, S.; Torcasio, R.C.; Corsi, A.; Di Carlo, P.; Dietrich, S. Impact of Climate Change on the "Trabocchi Coast" (Italy): The Trabocco Turchino Case Study. *Sustainability* **2023**, *15*, 10880. [CrossRef]
4. Mahoney, K. Extreme hail storms and climate change. *Bull. Am. Meteorol. Soc.* **2020**, *101*, S17–S22. [CrossRef]
5. D'Adderio, L.P.; Pazienza, L.; Mascitelli, A.; Tiberia, A.; Dietrich, S. A Combined IR-GPS satellite analysis for potential applications in detecting and predicting lightning activity. *Remote Sens.* **2020**, *12*, 1031. [CrossRef]

6. Chkeir, S.; Anesiadou, A.; Mascitelli, A.; Biondi, R. Nowcasting extreme rain and extreme wind speed with machine learning techniques applied to different input datasets. *Atmos. Res.* **2023**, *282*, 106548. [CrossRef]
7. Aruffo, E.; Di Carlo, P. Homogenization of instrumental time series of air temperature in Central Italy (1930–2015). *Clim. Res.* **2019**, *77*, 193–204. [CrossRef]
8. Yu, C.S.; Decouttere, C.; Berlamont, J. Storm Surge Simulations in the Adriatic Sea. In *CENAS: Coastline Evolution of the Upper Adriatic Sea Due to Sea Level Rise and Natural and Anthropogenic Land Subsidence*; Gambolati, G., Ed.; Springer: Dordrecht, The Netherlands, 1998; pp. 207–232.
9. Forlani, M.C. *Cultura Materiale e Progetto Sostenibile. Una Guida al Mantenimento dei Trabocchi della Costa Teatina*; Edicom Edizioni: Monfalcone, Italy, 2014.
10. Special Territorial Project 2023. Available online: https://www.provincia.chieti.it/flex/cm/pages/ServeBLOB.php/L/IT/IDPagina/9124 (accessed on 11 December 2023).
11. Latour, B. *Changer de Société, Refaire de la Sociologie*; La Découverte Poche: Paris, France, 2010.
12. Campos y Covarrubias, G. *Metodologías d la Investigación Cualitativa en las Ciencias Sociales: Etnografía, Historias de Vida, Estudios de Caso, Comunidad y Diagnóstico*; Universidad Nacional Autónoma de México Escuela Nacional de Trabajo Social: Ciudad de México, Mexico, 2017.
13. Corona Berkin, S. *Producción Horizontal del Conocimiento*; CALAS: Guadalajara, Mexico, 2020.
14. Forlani, M.C. *Progettare per l'ambiente Costiero. Il Recupero della Cultura Materiale e la Valorizzazione delle Risorse Nella "Costa dei Trabocchi"*; Edicom Edizioni: Monfalcone, Italy, 2022.
15. Cuzzucoli Crucitti, R. *La Costa dei Trabocchi nei Parlamenti, Statuti e Capitolari dei Feudi dell'Abbazia di S. Giovanni in Venere*; Edizioni Carabba srl: Lanciano, Italy, 2020.
16. The Amsterdam Declaration of 1975. Available online: https://humanists.international/policy/amsterdam-declaration-1952/ (accessed on 7 December 2023).
17. Farinelli, V.; Nicolai, N.C. *La Via Verde della Costa dei Trabocchi: Itinerari e Percorsi Lungo la Pista Ciclopedonale in Abruzzo*; Menabò: Ortona, Italy, 2022.
18. Available online: https://www.regione.abruzzo.it/content/piano-di-adattamento-ai-cambiamenti-climatici-pacc-abruzzo (accessed on 11 December 2023).
19. Cupido, P. *Trabocchi, Traboccanti & Briganti*; Edizioni Menabò: Ortona, Italy, 2003.
20. Marino, L.; Pignatelli, O.; Barone, P. *L'ingegnere Sopra e Sotto il Mare: La Fabbrica dei Trabocchi, Macchine per la Pesca Costiera*; DIDA Press: Florence, Italy, 2018.
21. Grbec, B. Climate change and Adriatic ichthyofauna. *Fish. Oceanogr.* **2020**, *9*, 187–191.
22. Santaloia, F.; Cotecchia, V.; Monterisi, L. Geological evolution and landslide mechanisms along the central Adriatic coastal slopes. In *Advances in Geotechnical Engineering: The Skempton Conference: Proceedings of a Three Day Conference on Advances in Geotechnical Engineering, Organised by the Institution of Civil Engineers and Held at the Royal Geographical Society, London, UK, on 29–31 March 2004*; Thomas Telford Publishing: London, UK, 2024; pp. 943–954.
23. Doglioni, A.; Galeandro, A.; Guerricchio, A.; Simeone, V. Tectonic Stress as Possible Co-predisposing Factor for Landslides Along the Central Adriatic Coast of Italy. In *Engineering Geology for Society and Territory-Volume 2: Landslide Processes*; Springer International Publishing: Cham, Switzerland, 2015; pp. 283–287.
24. Segrè, C. *Considerazioni Geognostiche Circa il Consolidamento della Ferrovia nei Tratti Franosi del Litorale Adriatico, Con Speciale Riguardo Alla Frana di Torino di Sangro*; Tip. Unione Ed.: Turin, Italy, 1918.
25. Cancelli, A.; Marabini, F.; Pellegrini, M.; Tonnetti, G. Incidenza delle frane sull'evoluzione della costa adriatica da Pesaro a Vasto. *Mem. Soc. Geol. Ital.* **1984**, *27*, 555–568.
26. Mascitelli, A. Progetto di Sviluppo Locale e Valorizzazione Ambientale del Territorio Teatino. Master's Thesis, Sapienza University of Rome, Rome, Italy, 2015.
27. Hersbach, H. The ERA5 Atmospheric Reanalysis. In *AGU Fall Meeting Abstracts*; Wiley: New York, NY, USA, 2016; NG33D-01.dataset.
28. Tiberia, A.; Mascitelli, A.; D'Adderio, L.P.; Federico, S.; Marisaldi, M.; Porcù, F.; Realini, E.; Gatti, A.; Ursi, A.; Fuschino, F.; et al. Time evolution of storms producing terrestrial gamma-ray flashes using ERA5 reanalysis data, GPS, lightning and geostationary satellite observations. *Remote Sens.* **2021**, *13*, 784. [CrossRef]
29. Di Carlo, P.; Aruffo, E.; Brune, W.H. Precipitation intensity under a warming climate is threatening some Italian premium wines. *Sci. Total Environ.* **2019**, *685*, 508–513. [CrossRef]
30. The Budapest Declaration on World Heritage of 2003. Available online: https://whc.unesco.org/archive/2002/whc-02-conf202-5e.pdf (accessed on 20 December 2023).
31. Available online: https://whc.unesco.org/archive/2007/whc07-31com-13be.pdf (accessed on 4 December 2023).
32. Corona Berkin, S. Flujos metodológicos desde el sur latinoamericano. La zona de la comunicación y las metodologías horizontales. *Comun. Soc.* **2017**, *30*, 69–106. [CrossRef]
33. Recht, R. *Penser le Patrimoine: Mise en Scene et Mise en Ordre de l'art*; Éditions Hazan: Paris, France, 2008.
34. Brandi, C. *Teoria del Restauro, Collana Piccola Biblioteca n. 318*; Einaudi: Torino, Italy, 1977.
35. Decreteto Legislativo Numero 42, 2004. Available online: https://www.normattiva.it/urires/N2Ls?urn:nir:stato:decreto.legislativo:2004-01-22;42 (accessed on 25 January 2024).

36. Cordaro, M. Restauro e tutela: Scritti scelti (1969–1999). In *Annali dell'Associazione Ranuccio Bianchi Bandinelli*; Griffiti editore: Roma, Italy, 2000; pp. 1–192.
37. Sardella, A.; Palazzi, E.; von Hardenberg, J.; Del Grande, C.; De Nuntiis, P.; Sabbioni, C.; Bonazza, A. Risk mapping for the sustainable protection of cultural heritage in extreme changing environments. *Atmosphere* **2020**, *11*, 700. [CrossRef]
38. Bonazza, A.; Sardella, A.; Kaiser, A.; Cacciotti, R.; De Nuntiis, P.; Hanus, C.; Maxwell, I.; Drdácký, T.; Drdácký, M. Safeguarding cultural heritage from climate change related hydrometeorological hazards in Central Europe. *Int. J. Disaster Risk Reduct.* **2021**, *63*, 102455. [CrossRef]
39. Available online: https://www.protecht2save-wgt.eu (accessed on 18 June 2024).
40. Cacciotti, R.; Sardella, A.; Drdácký, M.; Bonazza, A. A Methodology for Vulnerability Assessment of Cultural Heritage in Extreme Climate Changes. *Int. J. Disaster Risk Sci.* **2024**, *15*, 404–420. [CrossRef]
41. Grütter, J.K. *Basics of Perception in Architecture*; Springer Nature: Berlin/Heidelberg, Germany, 2020.
42. Bianco, L. Architecture, values and perception: Between rhetoric and reality. *Front. Archit. Res.* **2018**, *7*, 92–99. [CrossRef]
43. Hauge, Å.L. Identity and place: A critical comparison of three identity theories. *Archit. Sci. Rev.* **2007**, *50*, 44–51. [CrossRef]
44. Moqadam, S.; Nubani, L. From house to home: Exploring the spatial expression of social identity on traditional Shiraz houses. *Archnet-IJAR Int. J. Archit. Res.* **2024**, *18*, 81–101. [CrossRef]
45. Pang, T.; Wang, X.; Nawaz, R.A.; Keefe, G.; Adekanmbi, T. Coastal erosion and climate change: A review on coastal-change process and modeling. *Ambio* **2023**, *52*, 2034–2052. [CrossRef]
46. Appiotti, F.; Krželj, M.; Russo, A.; Ferretti, M.; Bastianini, M.; Marincioni, F. A multidisciplinary study on the effects of climate change in the northern Adriatic Sea and the Marche region (central Italy). *Reg. Environ. Change* **2014**, *14*, 2007–2024. [CrossRef]
47. Parete, G.; Bruno, M.F.; Calabrese, P.; Carlucci, R.; Chiarulli, M.; D'Onghia, G.; Fiore, A.; Fratino, U.; Longo, C.; Longo, F.; et al. Climate impacts and adaptation strategies for coastal erosion, aquaculture, and tourism along the Adriatic side of Apulia region. *Front. Clim.* **2024**, *6*, 1378253. [CrossRef]
48. Boicourt, W.C.; Ličer, M.; Li, M.; Vodopivec, M.; Malačič, V. Sea state: Recent progress in the context of climate change. In *Coastal Ecosystems in Transition: A Comparative Analysis of the Northern Adriatic and Chesapeake Bay*; Wiley: New York, NY, USA, 2020; pp. 21–48.
49. Cushman-Roisin, B.; Gacic, M.; Poulain, P.M.; Artegiani, A. (Eds.) *Physical Oceanography of the Adriatic Sea: Past, Present and Future*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2013.
50. Hochman, A.; Marra, F.; Messori, G.; Pinto, J.G.; Raveh-Rubin, S.; Yosef, Y.; Zittis, G. Extreme weather and societal impacts in the eastern Mediterranean. *Earth Syst. Dyn.* **2022**, *13*, 749–777. [CrossRef]
51. Menna, M.; Martellucci, R.; Reale, M.; Cossarini, G.; Salon, S.; Notarstefano, G.; Mauri, E.; Poulain, P.M.; Gallo, A.; Solidoro, C. A case study of impacts of an extreme weather system on the Mediterranean Sea circulation features: Medicane Apollo (2021). *Sci. Rep.* **2023**, *13*, 3870. [CrossRef] [PubMed]
52. Gonella, M.; Teatini, P.; Tomasi, L.; Gambolati, G. Flood risk analysis in the Upper Adriatic Sea due to storm surge, tide, waves, and natural and anthropic land subsidence. In *CENAS: Coastline Evolution of the Upper Adriatic Sea Due to Sea Level Rise and Natural and Anthropogenic Land Subsidence*; Springer: Dordrecht, The Netherlands, 1998; pp. 313–324.
53. Međugorac, I.; Pasarić, M.; Güttler, I. Will the wind associated with the Adriatic storm surges change in future climate? *Theor. Appl. Climatol.* **2021**, *143*, 1–18. [CrossRef]
54. Cavaleri, L.; Bertotti, L.; Buizza, R.; Buzzi, A.; Masato, V.; Umgiesser, G.; Zampieri, M. Predictability of extreme meteo-oceanographic events in the Adriatic Sea. *Q. J. R. Meteorol. Soc. J. Atmos. Sci. Appl. Meteorol. Phys. Oceanogr.* **2010**, *136*, 400–413. [CrossRef]
55. Gouritin, A. Matriz de análisis: Territorio y derechos humanos. In *Migrantes Climáticos en México*, 1st ed.; FLACSO: Ciudad de México, Mexico, 2021; pp. 67–113.

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Analysis in Terms of Environmental Awareness of Farmers' Decisions and Attitudes: Reducing Pesticide Use and Risks

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Abstract: Pesticide residues are a significant problem affecting the quality and safety of agricultural products in Turkey. This study aims to investigate farmers' risk perception regarding pesticide residues, including the primary factors that influence their behavior from the farmers' perspective. In addition, the main characteristics of pesticide residues encountered in the production of agricultural products against the current policy background is investigated to provide decision support to the Turkish government for improving the safe production of agricultural products. This paper uses a binary logistic model to analyze farmers' perceptions of pesticide residues using a cross-sectional dataset of 323 vegetable growers in Bursa, Turkey. Farmer characteristics and pesticide application behavior were more effective in reducing residual risk perceptions than farm characteristics. The effects of membership in a cooperative, average amount of pesticide used, location where the pesticide was purchased, application timing, and adherence to last spraying and harvest timing on the perception of residues were the largest. Farmers receive helpful but limited information from pesticide distributors. However, the primary source of information is not the advisors, which is why these grievances exist. The study results show that policymakers should support cooperatives, expand pesticide training, and make public extension services more effective and that pesticide dealers should conduct more frequent inspections.

Keywords: sustainable agriculture; pesticide residue; residue perceptions; agricultural pollution; attitudes; behaviors; knowledge

1. Introduction

In today's world, the use of pesticides and its consequences are always on the agenda. This will remain so because, in addition to the intensive use of pesticides in traditional agriculture, the controlled use of pesticides is permitted in good agricultural practice, and natural pesticides are used in organic farming. Unconscious and incorrect use of pesticides leaves residues in the products. Pesticide residues on vegetables and other foods caused by unintentional and erroneous spraying pose a serious risk to consumer health and the environment [1–3]. According to a study by the Environmental Working Group, strawberries were among the foods with the most pesticides in Turkey in 2023. It was found that 20 different pesticides were found in strawberries, which were the most contaminated food in 2023. The second most contaminated food was spinach. It was found that 1.8 times more pesticide residues were found in spinach than in other products. Foods on the list included kale, mustard greens, peaches, pears, nectarines, apples, grapes, peppers and hot peppers, cherries, blueberries, and green beans [4,5].

The residue problem affects not only one country but is also a priority issue among countries that maintain trade relations. Industrialized countries deal meticulously with pesticide residues, and they are systematically monitored. Products that do not meet the specific standards do not find buyers. All countries require pesticide residues to be below the maximum residue levels (MRLs). The Rapid Alert System for Food and Feed (RASFF) of the European Union (E.U.) reports unsuitable products due to pesticide residues

circulating in Europe. The RASFF issues notifications relating to risks deriving from food, food-contacting material, or feed or serious risks to animal health and to the environment derived from feed [6].

In Turkey, as in the rest of the world, the unconscious and, to some extent, uncontrolled use of pesticides can cause many problems regarding food safety and human health. The Non-Toxic Tables of the Civil Society states that there are still 13 active substances used in pesticides in Turkey that have been classified as "extremely hazardous", "very hazardous", and "possibly carcinogenic" by the World Health Organization [7].

As mentioned, the European Union Commission publishes non-conformities resulting from border and market controls on food and feed in the RASFF. The Ministry of Agriculture and Forestry also conducts inspections on the domestic market regarding pesticide residues. Information such as all food and feed companies throughout the country, inspections at these companies, samples taken, analysis results of the samples, administrative sanctions imposed on the companies, and import and export records are entered into the Food Safety Information System of the Ministry of Agriculture and Forestry. However, unlike the RASSF system, this information is not publicly accessible, i.e., the audit and analysis results are not shared with the public. Even pressure from non-profit institutions such as the Bugday Ecological Life Support Association and Toxic-Free Tables is insufficient to publicize this data [8].

The state's declarations show that the contaminated products are not sold in domestic markets. The state confirms that the products in question were burned, buried, or destroyed in various ways. However, the investigations carried out and the images published in the media show that these products are thrown into the sea, into bodies of water such as rivers and stream beds, onto empty fields, or left to rot in the fields. In these cases, the chemical compounds of the pesticides contaminate the water or soil and affect other agricultural products. Furthermore, production and consumption analyses claim that these rejected products have been placed in the domestic market. However, official figures have not been published in this regard. As a result, producers cannot be paid for their work, and the national economy suffers.

The Ministry of Agriculture and Forestry registers and licenses plant protection products (PPPs) in Turkey. The corresponding regulation was first published in 1975 [9]. The latest Regulation No. 32489 on the Licensing and Market Placement of Plant Protection Products came into force on 14 March 2024 [10]. Durmusoglu et al. [11] report that the definitions of biopreparations or biopesticides are not fully defined within the scope of this regulation. Regarding pesticides in Turkish legislation, the Turkish Food Codex Regulation on Maximum Residue Limits of Pesticides was published on 25 November 2016 [12].

Parallel to practices in the world, there is a wide range of legislation from production to storage and application of PPPs. In order for a PPP to be used in agriculture in Turkey, it must be applied in accordance with the licensing legislation and approved by meeting the legal requirements. However, this cannot prevent problems related to the handling of pesticides, especially in regions where agriculture is intensive, and product patterns vary. One of the problems with pesticide management in Turkey is that the active ingredients in the quantities of pesticides used are not adequately recorded. The data kept and shared annually by the District Directorates of Agriculture is based on pesticide groups such as insecticides, fungicides, etc., and not on active substances. This situation makes evaluating the pesticide active substances used according to their hazardous properties difficult. There are PPP database applications and formulation, barcode, and QR code applications. However, the fact that this practice is not applied in many parts of the country by the PPP distributors and thus also by the district agricultural directorates makes it difficult to record the quantities of pesticides used by active ingredient type and to control their use. This situation not only jeopardizes food safety within the country but also poses a residue problem in exported foodstuffs [13].

The collection and disposal of pesticide containers in Turkey are handled under the 'Hazardous Waste Regulation'. However, this regulation has not been sufficiently

implemented. Although this regulation emphasizes the recycling of waste such as pesticide containers by the manufacturing company, this has not been implemented in practice [14].

The use of pesticides in Turkey is lower than in other countries; nevertheless, the number of notifications for pesticide residues in exported food is relatively high. Of the countries that exported food to the E.U. in 2021, the Netherlands, for example, used 9.4 kg/ha of pesticides, while the number of notifications received by the RASFF was 240. In Turkey, pesticide use was 1.3 kg/ha. Despite this lower use, Turkey was the most notified non-member country, with a total of 630 notifications. The RASFF also issues notifications of non-compliance. These notifications concern non-compliance with food, food-contacting materials, or feed that do not pose a risk, non-serious animal health risks, or plant health or animal welfare risks. The most common pesticide residue issues escalated to the RASFF concerned compliance notifications for the use of pesticides in fruit and vegetables (430). Turkey was followed by India (383), of which 272 were pesticide notifications, and China (331), of which almost half (160) concerned food [15].

Studies show that farmers generally have moderate-to-good knowledge of the harmful effects of pesticides on the environment and human health. However, studies also show that they must know whether pesticides are safe. A study conducted in 2017 in the Gursu and Kestel districts of Bursa province aimed to determine the behavior of growers regarding the use of pesticides in fruit cultivation. The research results showed that 56.2% of the participants believed there would be residues if the interval between the last spraying and the harvest was not observed. In addition, 17.8% of the same growers believed that some pesticides leave residues [16]. In a recent study, pistachio growers were asked about the problem of pesticide residues. One-third of growers (33%) responded "They disappear when the rain washes them". Those who said "I do not know about residues" were 39%, and "residues" were 16%. The remaining 12% were of the opinion that pesticides leave no residue [17]. Almost half of the tomato growers (43.73%) believed the residues had no harmful effects. The rest of the participants believed that washing could remove residues (15.63%), that there are residues only when the pesticide is overdosed (15.63%), that all pesticides leave residues (15.63%), and that there are no residues when the recommended dose is used (9.38%) [18].

Farmers should not use pesticides over the doses specified in the technical instructions, should not apply more than the required pesticides, should not mix more than one pesticide, when necessary, should use appropriately calibrated spraying equipment, and should strictly observe the most critical point, i.e., the time between the last spray and harvest. However, there are indeed some things that could be improved in practice. It is important to recognize the potential use of sewage sludge as a pesticide-free fertilizer and to highlight its environmental benefits. Investigating the feasibility of using sewage sludge as a natural fertilizer represents an environmentally sound alternative in agricultural practice that warrants thorough investigation in research [19,20].

This study aimed to investigate farmers' risk perception of pesticide residues in a multidimensional way. The study and its results will guide young farmers, cooperative managers, food processors, advisors, and policymakers. The study will help them predict and understand farmer behavior and scientifically design and manage appropriate policies and programs.

Theoretical Framework and Research Assumptions

Several studies have extensively addressed extrinsic and intrinsic factors that influence farmers' behavior about pesticide safety and application. Nevertheless, research on the effects of perceptions of pesticide residues is limited [21–23]. In the present study, it is argued that farmers' perceptions could be influenced by their characteristics and the characteristics of the farm. In addition, the pesticide training received and previous pesticide use directly affect their perceptions. This study examined twenty-five factors considered antecedents of farmers' risk perceptions. The complexity of pesticide environmental and health impacts requires a multi-layered analysis of farmers' risk perceptions through a combined and

in-depth analysis of farmers' personal characteristics, farm-related characteristics, and current behavioral patterns.

The personal characteristics most frequently examined in current studies are farmers' age, education level, number of people in the family (or family labor force), and off-farm income. The empirical study by Sun et al. [24] found that the age of farmers negatively influenced the use of the correct pesticide dose. The authors found that older farmers were less likely to use the correct amount of pesticide. On the other hand, the age of Iranian vegetable farmers had a positive and significant effect on the perception of the risk of pesticide residues [22]. The formal education that farmers receive increases their awareness of environmental and health issues and positively affects their behavior regarding pesticide use and risk perception of pesticides. Farmers' education had a positive effect on the safety behavior of Nepalese farmers [25]. In addition to vegetable cultivation, the number of people in the household and money could influence farmers' risk perception. The study by Sun et al. [24] suggests that family size positively affects the correct use of pesticides by Chinese farmers. Wang and Liu [26] argue that farmers whose main source of income is farming are more resourceful in the dosage of pesticides. They may be better informed about pesticide standards and, therefore, less inclined to overuse pesticides.

In contrast, in another study in China, the regression coefficient for non-agricultural income was negative and significant at the 1% level. This indicates that farmers' willingness to reduce pesticide use decreased with increasing non-agricultural income [27]. Therefore, the first hypothesis is as follows:

H1. *Farmers' characteristics influence their pesticide residue perceptions*.

The effects of farm-related factors have been included in fewer studies. Studies have frequently investigated the effects of farming experience [28], farm size [22], and agricultural income [29] on pesticide usage behavior. On the other hand, land ownership [30] and cooperative membership [29] variables were included in a few studies.

Wang and Liu [26] argued that farmers whose primary source of income was agriculture were more resourceful about pesticide dosage. They might be more informed of pesticide standards and, therefore, less likely to overuse pesticides. Karabat and Atis [31] and Zhao et al. [32] argued that large-scale farms relied on robust vegetable income and were prone to apply pesticides excessively. In contrast, Zhu and Wang [33] research indicated that farm size significantly and negatively impacted pesticide usage intensity. Their research proved that, on average, a 1% increase in farm size leads to a 0.2% reduction in pesticide use per hectare. The probit regression results indicated that farming experience was negatively (and significantly) related to pesticide use intensity among farmers in Kuwait [34].

Joining farmers' cooperatives can help farmers to reduce pesticide use. Cooperatives can reduce pesticide overuse through standard requirements, in-cooperative training, and audit mechanisms. Indeed, the findings of Zhao et al. [29] confirm this argument. Further, Jin et al. [35] note that the lowest pesticide use is achieved when farmers are provided with accurate information and trust this information provider. Cooperative members have a very high level of trust in their retailers. This trust and precise information lead to the lowest pesticide use.

Mehmood et al. [22] and Baharom et al. [30] found that land ownership does not affect farmers' pesticide residue risk perceptions. Additionally, an analysis of Migheli's [36] research with Vietnamese farmers suggests that farmers would use less pesticides if they had higher farming incomes. The author underlines that using chemical products is necessary to reach some income level but emphasizes that once a certain income level is reached, the use of agricultural chemicals does not increase with income. In the study of Uzundumlu et al. [37], however, pesticide usage decreased as the unit income of hazelnut producers and the amount of hazelnut obtained increased. Still, this decrease was statistically significant. Following the above, the second hypothesis is as follows:

H2. *Farm characteristics influence farmers' perceptions of pesticide residue.*

The demographic and farm characteristics mentioned above are influential in the inappropriate and excessive use of pesticides. However, the farmers' residue perceptions often formed as an extension of their past and current behaviors. Farmers with high-risk perceptions, i.e., those who worry that pesticides will leave residues (on and in the products, depending on their forms), are expected to be more careful in their pesticide handling behavior.

Pesticide use behavior encompasses a multi-stage complex series of behaviors. Although it made the analysis and interpretation difficult, this research attempted to incorporate many of these behavioral features into the model to gain deeper insight. Working more than 6 h a day significantly reduces farmers' use of the correct procedure during application [38]. Numerous studies have shown that pesticide dealers are farmers' primary information sources on pesticides. Jallow et al. [34] observed that farmers were more likely to overuse pesticides if pesticide dealers were their primary information source about pesticide use. The regression results of Jin et al.'s [39] study on the pesticide use of small-scale farmers in China showed that reading the label on the pesticide containers negatively affected pesticide overuse. This finding is predictable and coherent. If farmers read pesticide container labels before usage, they would be more inclined toward using the recommended dose and reducing the probability of pesticide overuse. Wu and Hou's [23] research underlined that considering safety intervals during pesticide application significantly affected farmers' pesticide residue perceptions. Therefore, the third hypothesis is as follows:

H3. *Past pesticide application behavior influences farmers' pesticide residue perceptions.*

Training and advice, directly and indirectly, impact farmers' perceptions by influencing their specific actions concerning health and environmental safety. Training on pesticides significantly improves farmers' intention to comply with pesticide regulations [30]. Stricter compliance reduces the excessive use of pesticides [34]. Migheli [36] states that poor education and a lack of specific training leads to the overuse of agricultural chemicals. Farmers' awareness of pesticide residues can be improved through training. In fact, IPM training has positively and significantly influenced the risk perception of Pakistani farmers regarding pesticide residues [22]. The fourth and final hypothesis is as follows:

H4. *Pesticide training influences farmers' pesticide residue perceptions.*

This research provides a theoretical model of the critical factors influencing farmers' perceptions of pesticide residues. The theoretical model considers farmers' perceptions of pesticide residues as the dependent variable and farmers' characteristics, farming characteristics, past pesticide application behavior, and pesticide training as dependent variables.

Personal characteristics included age and years of formal education, family size, and other sources of income besides vegetable farming; farm characteristics included land size, land ownership, farming experience, agricultural income, agricultural expenditure, and membership in a cooperative. Farmers' past pesticide application behavior included pesticide application experience, number of applications per year, average application time per spray day, average application amount per spray day, and meter used. Behavioral variables also included who recommended the dosage used when spraying, where the product was obtained from, whether the pesticide was used at the recommended dosage, when the pesticide was applied, whether the waiting time between two sprays was observed, whether the waiting time between spraying and harvest was observed, what was carried out if it was not effective, whether the label on the pesticide container was read, and whether multiple pesticides were mixed. Finally, pesticide training provided by government agricultural extension services or cooperatives was also included in the model.

2. Materials and Methods

2.1. Questionnaire Development and Data Collection

Farmers' opinions on the use of pesticides can vary greatly depending on the product. The author focused exclusively on vegetable producers to avoid sampling errors. The preliminary draft of the questionnaire was prepared considering the existing literature [22] and the researchers' previous experiences. A panel of three experts in crop protection, occupational medicine, and public health reviewed the questionnaire to determine content validity. The questionnaire contained closed-ended questions to obtain meaningful information from the vegetable growers. The dependent variable was farmers' risk perception of pesticide residues, assuming that consumer health is at risk from pesticide residues. It was measured as a dummy variable (if the farmer believed that there were no residues when pesticides are used at the recommended dose, the value was 1; otherwise, it was zero). The effects of 25 independent variables were assessed in the survey (Table 1).

Table 1. Description of variables and social and demographic characteristics of the farmers.

Variable	Abbreviation	Definition	Mean ***
Farmers' perception of pesticide residues (Dependent variable)	residue	1 = There will be no residues if the pesticide is used in the recommended dose; 0 = Otherwise	Yes: 166 (51.4%); No: 157 (48.6%)
Age of the farmers	age	Age in years	M = 51.13 SD = 11.06
Educational level	edu	Education in years	M = 6.76 SD = 3.06
Family size	famsize	No. of family members	M = 4.55 SD = 2.00
Income outside crop prod.	noncrop	1 = Yes; 0 = No	N = 249 (77.2%)
Years in farming	farmexp	Years	M = 29.36 SD = 13.42
Cooperative membership	coopmem	1 = Yes; 0 = No	N = 234 (72.4%)
Size of the land	landsize	Hectares	M = 09.12 SD = 213.51
Land ownership	landown	1 = Owned; 0 = Leased	N= 168 (52.0%).
Agricultural income	agriscience	USD **; per year; (000)	M = 84.98 SD = 91.98
Agricultural expenditure	agricexp	USD **; per year; (000)	M = 49.10 SD = 58.05
Spraying experience	pestexp	Years	M = 18.95 SD = 10.95
Number of spraying	numpestapp	Days (per year)	M = 15.94 SD = 33.69
Spraying time	avapptime	Hours (per day)	M = 5.56 SD = 15.94
Pesticide amount used	avpestuse	lt (per day)	M = 5.26 SD = 4.90
Measuring device	mesdevice	1 = Measurement container; 0 = Else	N = 292 (90.4%)
Dosage decision source	dosages	1 = Pesticide dealer; 0 = Else	N = 124 (38.4%)
Pesticide purchase place	purchaseplc	1 = Pesticide dealer; 0 = Cooperative	N = 296 (91.6%)
Application dosage	appdosage	1= Recommended dosage; 0 = Overdosage	N = 296 (90.1%)
Application time	apptime	1 = When pest presence was observed; 0 = Else	N = 160 (49.5%)
Obey wait time between sprayings	obywaittime	1 = Yes; 0 = No	N = 309 (95.7%)
Obey wait time between last spraying and harvest	obylastspr	1 = Yes; 0 = No	N = 316 (97.8%)
If the pesticide is not effective	pestnoteffct	1 = Exchange with stronger pesticide; 0= Else	N = 201 (62.2%)
Pesticide training	pesttraining	1 = Yes; 0 = No	N = 100 (31.0%)
Reading labels	readlabel	1 = Yes; 0 = No	N = 212 (65.6%)
Mixing products	mixingpest	1 = Yes; 0 = No	N = 219 (67.8%)

M: mean; SD: standard deviation; N: number of respondents. ** Calculated with the Central Bank exchange rate dated 15 July 2019. *** For categorical values, the referenced category is given.

For the pilot survey, ten farmers were interviewed whose results were not included in this study. The questionnaire was modified to reflect farmers' attitudes and behaviors based on the pretest and feedback received. The interviewees were selected from among Bursa Uludag University, Faculty of Agriculture graduate students to collect the required information. Before the interviews, the students were trained and informed about what to pay attention to when communicating with the farmers. The questionnaire consisted of four parts. The first part contained demographic questions. The second part contained

questions aimed at identifying farmers' attitudes and behaviors regarding the impact of pesticides on the environment and the characteristics of pesticide use. The third part contained questions about the products grown, the pests and pesticide types, the amount used, and the frequency of spraying. The fourth part concerned the sprayers' working practices during preparation and spraying and after spraying. The approval of the ethics committee was obtained before the survey was conducted.

The survey was conducted using a multi-stage sampling method. At the first stage, a stratified random sample was used. Four cities in Bursa province where vegetables are mainly grown were selected: Yenisehir, Karacabey, Kemalpasa, and Inegol. These four districts accounted for 67% of the province's vegetable production [40]. At the second stage, one town from each stratum, the villages within the selected towns, and the vegetable producers per village were selected. At the third stage, a random sample was drawn, and a sample of 323 vegetable and fruit farmers was identified. Sixty-two farmers were from Mustafakemalpasa, 33 from Yenisehir, 52 from Karacabey, and 176 from Inegol. The survey was conducted between October 2022 and March 2023. However, care was taken to ensure that the surveys were conducted during the peak spraying season. Before conducting the survey, the heads of the concerned villages and cooperative branches were informed about the nature and purpose of the survey. The farmers were assured that the study was for academic purposes and that their responses would be treated confidentially.

2.2. Data Analysis

All data obtained from the survey questionnaires were coded and analyzed using the SPSS 28.0 package program. Cronbach's alpha (α) was calculated as $\alpha = 0.822$. This conclusion fulfills the criterion of survey reliability. Chi-square and correlation analyses were used to check for possible associations between the survey variables. We used $\alpha \leq 0.05$ as the statistical significance criterion in all the data analyses. Spearman's and point biserial correlation tests were used to determine the level of correlation and significance of the relationship between farmers' risk perceptions of pesticide residues and their socioeconomic farm characteristics and spraying behavior. We conducted a regression analysis using the binary logistic model to identify the factors influencing farmers' risk perceptions of pesticide residues.

Logistic regression is used when the dependent variable is categorical and the independent variables are categorical, continuous, or a combination of both. The dependent variable can be dichotomous or polytomous. The logistic regression used is binary if the dependent variable is binary. Logistic regression analysis is a successful and flexible statistical method for creating models with a categorical dependent variable. The flexibility of the method stems from the fact that it requires far fewer assumptions than similar statistical methods. The logistic regression model has no requirements such as a normal distribution of the explanatory variables, a linear relationship between them, or an equal variance of the different categories. In addition, the explanatory variables can be discrete, continuous, or 0–1 variables. Logistic regression focuses on the probability of a certain expected result occurring for each observation unit.

The logistic regression model is based on the odds ratio. The odds ratio compares the probability of an event occurring with the probability that the event will not occur. The logistic regression model is therefore obtained by taking the natural logarithm of the odds ratio. The maximum likelihood method is often used to estimate the parameters of the logistic regression model obtained [41]. The binary logistic regression model is as follows:

$$\begin{aligned} P_i = E(Y_i = 1|X_i) = F(I_i) = F(\beta_0 + \beta_1 X_i) \\ = \frac{1}{1+e^{-I_i}} \\ = \frac{1}{1+e^{-[\beta_0+\beta_1 X_i]}} \end{aligned} \quad (1)$$

It takes a value between $-\infty$ and $+\infty$, and P_i takes a value between 0–1, so a non-linear relationship is observed between P_i and I_i.

Equation (1) is non-linear for both X_i and coefficients. In such a case, since an estimation cannot be made with the O.L.S. (ordinary least squares) method, the equation should be converted to a linear form. $e^{-I_i} = \frac{1-P_i}{P_i}$ is obtained by multiplying both sides of the equation by $1 + e^{-I_i}$, dividing P_i, and subtracting 1. Since e^{-I_i} is $\frac{1}{e^{I_i}}$, finally, $e^{I_i} = \frac{P_i}{1-P_i}$ is obtained. This final equation obtained is the odds ratio. By taking the natural logarithm of both sides of this equation:

$$L_i = ln\left(\frac{P_i}{(1-P_i)}\right) = I_i = \beta_0 + \beta_1 X_i \quad (2)$$

is obtained. Thus, the logarithm of the probability ratio, L_i, is no longer only linear for X_i but also for the coefficients. One unit change in X changes the log probability ratio (L_i) by β_1.

The odds ratio is expressed as Exp(β) in the logistic regression model. Since the odds ratio is the ratio of the probability of an event occurring to the probability of it not occurring, Exp(β) indicates how often the Y variable is likely to be observed with the effect of the X_i variable or by what percentage [42].

The rate of probability change for the independent variable depends not only on the corresponding coefficient (β) but also on the probability level at which the change was measured. Therefore, while the other variables are constant in the logistic regression model, the marginal effects for each variable are obtained with Equation (3). [43].

$$\frac{dP_i}{dX_i} = P_i(1-P_i)\beta_1 \quad (3)$$

The SPSS 28.0 and Stata/SE 15.0 software were used for the data analysis.

3. Results

3.1. Socioeconomic Characteristics of Farmers

The socioeconomic characteristics of the farmers surveyed are listed in Table 1. A whopping 86% of the farmers in the surveyed regions were above 40 years of age, and 23.5% were above 60 years of age. A total of 63.2% of them had primary education or less. The average family size was 4.55. A significant proportion of the participants (77.2%) had an income in addition to vegetable production, and 46.3% of this income was a pension. The average farming experience was 30 years; most participants were cooperative members (72.4%).

The average farm size was 9.12 hectares. Half of the farmers surveyed (52%) farmed their own land, while the other half (48%) were tenants or sharecroppers. While the average annual agricultural income of the farmers was USD 85,000, their average annual agricultural expenditure was USD 49,000. The research results show that most of the participants' socioeconomic characteristics aligned with the average values for Turkey [16,17]. The research sample is, therefore, representative.

3.2. Farmers' Understanding of Risk Perception and Pesticide Residues

Table 2 contains the questions used to assess the farmers' perceptions and attitudes towards pesticide residues. The vegetable growers in the study were highly aware that the use of 'high doses of pesticides increase the possibility of poisoning' (90.1%) and that 'some pesticides can cause fatal poisoning' (91.3%). Pesticide distributors often warn farmers about the toxicity levels, which are indicated on the labels. For this reason, the farmers were highly aware of the need to wear protective clothing when preparing and applying the pesticide (87.6%). However, many studies have repeatedly shown that farmers neglect or only partially use protective equipment [44,45]. A study conducted in Nigeria highlights that 49.3% of cocoa producers were aware that the products they handle are hazardous [46].

However, when asked if they took the necessary precautions, 94% answered 'no'. In Turkey, pesticides are mainly sourced from pesticide dealers, cooperatives, and provincial and district agricultural directorates. These organizations must have a license and be agricultural engineers. Because of this, there can be a misconception in farmers' minds that

the pesticides sold in licensed facilities are safe regardless of their age of use. Although most farmers knew that not every pesticide offered for sale is safe, it is thought-provoking that almost a third (28.7%) were unaware of this. The survey showed that the farmers were aware that the pesticides available for sale have different toxicity levels and that there may be safety issues depending on the application. Around half (46.7%) believed that all pesticides have the same harmful effects on health. Only 58.1% of vegetable and fruit growers in the north of the Delta, Egypt, had general knowledge about the harmful effects of pesticides on human health. The percentage of those who knew that not all compounds have the same harmful effects was 32.6% [47]. Again, half of the farmers (54.2%) believed that the pesticides would disappear in nature over time, and they did not mind walking in the sprayed area a few hours after spraying (42.1%). Similarly, 63.4% of tomato growers in Buea, Cameroon, stated that they saw no harm in re-entering the field less than 48 h after spraying [48]. These results show that farmers have little awareness of the risks of pesticides and that their knowledge of pesticides is very low.

Table 2. Farmers' pesticide risk perception.

Perception	Percentage (%)	
	Yes	No
If the pesticide is on sale, it is safe no matter how it is used.	28.7	71.3
High doses of pesticide use increase the possibility of poisoning.	90.1	9.9
All pesticides have the same adverse effect on health.	46.7	57.3
Some pesticides may cause fatal poisoning.	91.3	8.7
Pesticides decompose in nature over the years	54.2	45.8
Protective clothing is necessary to prevent pesticide poisoning.	87.6	12.4
Entering the field a few hours after applying the pesticide is okay.	42.1	57.9

Source: field survey, 2023.

Table 3 shows the results of the correlation coefficients between the farmers' risk perceptions of pesticide use, personal and farm characteristics, and spraying behavior. The analysis shows that the farmers' risk perceptions correlated significantly and positively with the following variables: age, farming experience, additional income outside vegetable production, experience in pesticide application, and adherence to waiting time between sprays at the 0.01% level of significance, while the average time spent on pesticides per spraying day was significant at the 5% level. In contrast, the farmers' perception of risk showed a negative and significant association with the number of pesticide applications per year and farm size ($p < 0.001$), formal education, and where to seek advice on dosage decisions ($p < 0.05$).

Table 3. Correlation coefficients between farmers' risk perceptions and research variables.

Variables	Correlation Coefficient	*p*-Value	Correlation Type
age	0.270	0.000	Spearman
edu	−0.137	0.014	Spearman
famsize	−0.302	0.000	Spearman
farmexp	0.367	0.000	Spearman
coopmem	0.168	0.002	Point biserial
landsize	−0.094	0.143	Spearman
landown	−0.005	0.924	Point biserial
agricinc	0.089	0.110	Spearman
agricexp	0.090	0.108	Spearman
noncrop	0.268	0.000	Point biserial
pestexp	0.197	0.000	Spearman
numpestapp	−0.354	0.000	Spearman
avapptime	0.141	0.012	Spearman

Table 3. *Cont.*

Variables	Correlation Coefficient	*p*-Value	Correlation Type
avpestuse	0.079	0.284	Spearman
mesdevice	0.056	0.314	Spearman
dosages	−0.112	0.045	Spearman
purchaseplc	−0.061	0.275	Point biserial
appdosage	−0.104	0.063	Point biserial
apptime	0.167	0.003	Spearman
obywaittime	0.262	0.000	Point biserial
obylastspr	0.091	0.104	Point biserial
pestnoteffct	0.143	0.010	Spearman
pesttraining	0.147	0.008	Point biserial
readlabel	0.022	0.698	Point biserial
mixingpest	−0.043	0.436	Point biserial

3.3. Factors Affecting Farmers' Pesticide Residue Risk Perceptions

The results of the binary logistic analysis conducted to estimate the factors influencing farmers' perceptions of pesticide residues are shown in Tables 4 and 5. The explanatory variables were binary and focused on the factors influencing the farmers' perceptions of pesticide residues. Other statistical results, including pseudo R^2 measures (0.53), log-likelihood statistics (−32.51), and L.R. $X^2(25)(72.13)$, show the good fit of the binary logistic model.

Table 4. Estimated farmers' risk perception of pesticide residues using a binary logistic model.

Pest Residue	Odds Ratio	Std. Err.	z	$p > \|z\|$	[95% Conf. Interval]	
					Lower Bound	Upper Bound
age	4.787786	4.48442	1.67	0.095	0.7636026	30.0194
edu	0.0228149	0.0327243	−2.64	0.008	0.0013719	0.3794269
famsize	0.6445604	0.1396716	−2.03	0.043	0.4215162	0.9856276
noncropinc	2.90×10^{-10}	1.67×10^{-9}	−3.82	0.000	3.69×10^{-15}	0.0000228
farmexp	0.9311048	0.0339406	−1.96	0.050	0.8669032	1.000061
coopmem	2.224707	0.7982873	2.23	0.026	1.101128	4.494774
landsize	0.9972335	0.0033269	−0.83	0.406	0.9907341	1.003776
landown	1.157374	0.8803755	0.19	0.848	0.2606116	5.139893
agriscience	1.010105	0.0265671	0.38	0.702	0.9593533	1.063541
agricexp	0.8893803	0.0679314	−1.53	0.125	0.7657239	1.033006
pestexp	1.019844	0.0462972	0.43	0.665	0.9330233	1.114744
numpestapp	0.453821	0.1571479	−2.28	0.023	0.2302145	0.8946154
avapptime	0.3457142	0.1436586	−2.56	0.011	0.1531115	0.7805969
avpestuse	2.338539	0.689732	2.88	0.004	1.311868	4.168686
mesdevice	0.557945	0.4295438	−0.76	0.449	0.1233897	2.522922
dosages	0.3235526	0.1706172	−2.14	0.032	0.1151027	0.9095034
purchaseplc	8.603046	6.4021	2.89	0.004	2.000859	3.699032
appdosage	0.0011836	0.0028846	−2.77	0.006	9.97×10^{-6}	0.1404999
apptime	6.131452	4.055154	2.74	0.006	1.677277	22.41413
obywaittime	0.0028453	0.0085194	−1.96	0.050	8.04×10^{-6}	1.006517
obylastspr	4.513748	4.761153	3.09	0.002	1.101128	4.494774
pestnoteffct	0.2834684	0.2130379	−1.68	0.093	0.0649819	1.236564
readlabel	8.833142	13.61492	1.41	0.158	0.4306456	181.18
mixingpest	0.2615257	0.325522	−1.08	0.281	0.0228045	2.999218
pesttraining	0.0070978	0.0162734	−2.16	0.031	0.0000793	0.6349067

The predictors for personal characteristics were age, education level, family size, and whether the family has additional income for vegetable production. The level of education, family size, and additional household income (excluding vegetable production) were negatively related to the likelihood that the farmers would perceive the risk of pesticide residues. When the other factors were held constant, the logarithm of the ratio of the

probability of perceiving residue risk decreased by 0.023 (0.645 and 2.9, respectively) when the education and non-farming variables changed by one unit. The education and non-farming variables were significant at the 1% level, with a marginal effect of −0.390 (and −2.268). Non-farming was significant at the 5% level, with a marginal effect of −0.009. In general, it is expected that a higher education level, larger family size, and additional money coming to the household should increase farmers' risk perception of arrears. The results show the opposite.

Table 5. Marginal effects of farmers' risk perceptions of pesticide residues.

Pestresidue	dy/dx	Std. Err.	z	$p > \|z\|$	[95% Conf. Interval]	
					Lower Bound	Upper Bound
age	0.1617578	0.0920387	1.76	0.079	−0.0186347	0.3421502
edu	−0.3904681	0.1276442	−3.06	0.002	−0.6406461	−0.1402902
famsize	−0.0453632	0.0209554	−2.16	0.030	−0.0864351	−0.0042913
nonfarminc	−2.268447	0.4242665	−5.35	0.000	−3.099994	−1.4369
farmexp	−0.0126703	0.0060379	−2.10	0.036	−0.0245044	−0.0008362
coopmem	0.1863095	0.0801636	2.32	0.020	0.0291917	0.3434273
landsize	−0.0002861	0.0003403	−0.84	0.400	−0.000953	0.0003807
landown	0.0150961	0.0785583	0.19	0.848	−0.1388754	0.1690676
agricinc	0.0010385	0.0027123	0.38	0.702	−0.0042775	0.0063544
agricexp	−0.0121086	0.0075969	−1.59	0.111	−0.0269982	0.002781
pestexp	0.0034878	0.0080351	0.43	0.664	−0.0122608	0.0192363
numpestapp	−0.0816038	0.0322524	−2.53	0.011	−0.1448173	−0.0183904
avapptime	−0.1097078	0.037837	−2.90	0.004	−0.1838669	−0.0355487
avpestuse	0.0877468	0.0258462	3.39	0.001	0.0370893	0.1384044
mesdevice	−0.0602687	0.0786899	−0.77	0.444	−0.2144979	0.0939606
dosages	−0.1165508	0.0492759	−2.37	0.018	−0.2131298	−0.0199717
purchaseplc	0.4673314	0.1476689	3.16	0.002	0.1779058	0.7567571
appdosage	−0.6960851	0.2135264	−3.26	0.001	−1.114589	−0.2775811
apptime	0.1873078	0.0582298	3.22	0.001	0.0731794	0.3014362
obywaittime	−0.6054904	0.289222	−2.09	0.036	−1.172355	−0.0386257
obylastspr	1.453427	0.3881154	3.74	0.000	0.6927348	2.214119
pestnoteffct	−0.1302119	0.072237	−1.80	0.071	−0.2717937	0.0113699
pesttraining	−0.5110716	0.2209726	−2.31	0.021	−0.94417	−0.0779733
readlabel	0.2250165	0.153895	1.46	0.144	−0.0766122	0.5266451
mixingpest	−0.1385337	0.1251002	−1.11	0.268	−0.3837255	0.1066581

Membership in a cooperative, farmland ownership, and agricultural income increased farmers' perceptions of residual risk. In contrast, farming experience, acreage size, and farming expenses decreased farmers' perceptions of residual risk. However, only cooperative membership and farming experience were not statistically significant at the 5% level. For a one-year increase in farming experience, the logarithm of the probability of residual risk perception decreased by 0.0911. If the farmer was a cooperative member, the logarithm of the ratio of the probability of residual risk perception increased by 2.224.

Research has shown that farmers' behavior when applying pesticides influences their risk perceptions. Most of the variables included in the model had a statistically significant effect on the dependent variable. The number of sprays carried out during the year and the average duration of spraying on each spraying day significantly affected the farmers' perceptions of residual risk at the level. As the number and duration of pesticide applications increased during the year, the farmers' perception of pesticide risk increased, i.e., their perceptions that the pesticides applied will leave residues. When the variables numpestapp and numpestapp increased by one unit, the logarithm of the ratio of the probability of the perception of the residue risk decreased by 0.023 (or 0.345). Farmers who consulted the pesticide dealer when deciding on the pesticide dose, used the recommended dose, and followed the recommended waiting time between sprays had a lower perception of pesticide risk, i.e., the perception that pesticides leave less residue in these situations was

higher. When the variables dosage, application, and waiting time were increased by one unit, the logarithm of the ratio of the probability of perceiving the risk of residue decreased by 0.32, 0.001, and 0.002, respectively.

Farmers who bought pesticides from dealers, used the recommended dosage, and observed the waiting period between the last spraying and harvest were less concerned that pesticides may contain residues. For a one-unit change in the purchaseplc (or app time and oblasts) variables, the logarithm of the odds ratio of pesticides containing residues increased by 8.603 (or 6.131 and 4.513). These variables also had the highest marginal effects (0.467, 0.187, and 1.45, respectively). Most of these variables were significant at the 5% and 1% levels, suggesting that the farmers' behavioral habits directly and significantly impacted the farmers' risk perception.

Specialized pesticide handling training was inversely related to the farmers' risk perceptions of residues. Farmers who had participated in pesticide training were more likely to believe that there will be no residues if the recommended amount is not exceeded. For a one-unit change in the variable pesticide training, the logarithm of the ratio of the probability of perceiving the risk of residues decreased by 0.007. Training was significant at the 5% level, with a marginal effect of −0.511.

4. Discussion

Farmers' risk perception of pesticides is one of the most important factors in promoting the safe use of pesticides and ensuring food safety. Studies conducted in Turkey have frequently investigated farmers' pesticide use habits, their mistakes in pesticide use, and their reckless attitude towards personal protection. These studies have emphasized the role of cooperatives, label reading, and proper training to improve farmers' risk perception.

This study aimed to investigate the risk perceptions of vegetable farmers in Bursa province regarding pesticide residues, and further research data are needed from the literature. The research findings will provide new perspectives on the factors influencing farmers' risk perceptions of pesticide residues. The author first discusses the relationship between farmers' personal and farm characteristics and pesticide application behavior, as well as the role of education in understanding pesticide residue risk perceptions. Several valuable guidelines for local and national policymakers, farmers, advisors, and cooperatives are then presented.

The coefficients of the binary logistic model represent the farmers' characteristics (family size, additional income outside vegetable production) and had a positive and significant influence on the risk perceptions of pesticide residues. However, formal education had a significant but negative influence on risk perceptions, confirming Hypothesis 1.

Studies have shown that a higher level of education increases the likelihood that farmers will apply the correct dose [25] and comply with pesticide regulations [30]. It was expected that higher levels of education would also increase the farmers' knowledge that pesticides do not leave residues (above MRLs) on crops. However, our results showed the opposite; the farmers' risk perception decreased as their level of education increased. Mehmood et al. [22] came to the same conclusion. With increasing formal education, farmers' risk perception regarding pesticide residues in Pakistan decreased. The reason for this is that as the level of education increases, farmers become more confident in production and aim to increase yield, for which they use more pesticides and ignore the residue problem in the short term.

As the family grows, so does the number of dependents. Consequently, farmers will try to secure the yield, so they will use more pesticides. Therefore, their risk perception will decrease. Wang and Liu [26] also came to a similar conclusion in their research in China. The risk perception of farmers decreased with increasing family size.

This study shows that the risk perception of pesticides increases as farmers' income increases. On the contrary, the literature emphasizes that farmers with a high non-agricultural income are less dependent on agricultural income. Our results may seem contradictory, yet 56.3% of the farmers in this study were 51 years old and older, and 23.5% were 61 years

old and older. Furthermore, 46.2% of their non-farm income was a pension. Farmers who relied only on pensions still took care of their produce and had a higher perception of risk.

Research often claims that farm characteristics influence farmers' pesticide use behavior. However, Table 5 shows that only farming experience (negative) and membership in a cooperative (positive) significantly influenced the farmers' risk perceptions regarding residues. The results only weakly support Hypothesis 2. More experienced farmers are generally older and less educated. They are less open to new developments and rely more on their experience than on advisors; therefore, their risk perceptions are lower. This finding is supported by recent research. Experienced farmers are more inclined to overuse pesticides [35], focus more on the benefits of pesticide use, and, therefore, have a lower perception of risk.

Membership in a cooperative increases risk perception by helping farmers reduce the overuse of pesticides. Cooperatives encourage farmers through training and effective communication to practice proper pesticide management to meet the cooperative's standards. Research in China [29], Turkey [37], and Oman [49] has also found an inverse relationship between joining cooperatives and farmers' behavior in excessive pesticide use.

Pesticide application involves a series of complicated behaviors, from choosing the right pesticide to preparation and application. The choices made at each stage have an impact on residue levels. Numerous studies have independently examined these behaviors and reported problems. The current research included as many variables as possible in the model to predict these complicated behaviors. Each behavior is interconnected, and the effects of a single behavior should be considered together with others. Nine of the fourteen variables in the model had a statistically significant impact on the growers' perceptions of pesticide residue risk. Thus, Hypothesis 3 is confirmed.

Spraying experience is often related to farming experience. In this study, the average farming experience of the farmers was 29 years, and their experience with spraying was 19 years. Theoretically, it can be assumed that farmers can spray better with increasing experience. In this study, experience in the use of pesticides increased the farmers' perception of risk. However, this increase was not statistically significant.

The number of spraying operations per year, the duration of the spraying operations on each working day, and the quantity used influence the amount of residue. This study showed that the participating farmers sprayed for an average of more than five hours per working day. This result is consistent with a study that found that most (67%) cocoa farmers in southwestern Nigeria worked for 6–8 h per day [46]. Such a long spraying time increases the risk of residues as farmers are distracted and ignore the spraying instructions.

A Chinese study reported that only 1.1% of wheat farmers were sufficiently informed about pesticide residues; 33.8% had never heard of pesticide residues, and the remaining respondents (63%) had some knowledge [21]. When Egyptian growers were asked if pesticides leave residues on crops, 27.7% answered yes, and a worrying 61.7% said they were unsure if pesticides leave residues [50]. About half of Iranian farmers (47.9%) had never heard of pesticides leaving residues, while the other half had no idea (41.8%). When asked whether pesticides harm agricultural products, 64.0% of Iranian farmers answered no, and 21.5% said they did not know [51].

Farmers obtain the necessary information on crop protection from various sources, including dealers, cooperatives, extension agents, neighboring farmers, and the media. Research shows that licensed dealers also act as agricultural extension agents. In a study conducted in the Wei River basin in China, 90 traders answered 'yes' when asked if they advised farmers on purchasing crop protection products [52]. In Turkey, 80% answered 'yes' [53]. Pesticide dealers are a convenient source of information in many regions, as the number of agricultural advisors is insufficient, and not all farmers know the scope of their services. It is feared that traders may be biased in recommending their products rather than encouraging farmers to make independent decisions about pest control methods. Concerns have also been raised that some distributors may encourage farmers to buy their products instead of using chemical products or products from other companies. However,

dealers in Turkey must have a college degree and be agricultural engineers. This is the most encouraging factor that motivates farmers to use distributors.

For this reason, the risk perception of farmers who bought pesticides from distributors was eight times higher. Pesticide distributors are also trusted sources worldwide. For example, 75% of farmers in Kuwait [34], 59% of farmers in Cameroon [54], 56.5% of farmers in the Wei River basin, China [52], and 52.6% of farmers in south India [55] trusted distributors to obtain information about pesticides.

Farmers not only buy from dealers but also apply the dose they recommended. As explained earlier, without effective extension services, dealers become the first and most reliable qualified source for farmers. Research shows that 38.4% of farmers determine application doses according to the vendor's recommendation. The managers of pesticide dealers in Turkey were asked about the people and institutions that affect farmers' pesticide selection choices. Like the current study's findings, 31.15% of the participants stated that the producers chose pesticides with the dealers' suggestions [56].

The pesticide label and usage instructions are critical information sources for correct application. Reading the label on the container negatively affects pesticide overuse and positively affects risk perceptions. If farmers read the label and instruction manual, they will be more likely to use the recommended dose, reducing the likelihood of pesticide overuse and residue [39]. Although reading the instructions for use in the current study also increased the pesticide risk perception eightfold, the fact that this effect was not statistically significant may be because the farmers also referred to the dealers' opinions simultaneously.

Most pesticides are extremely dangerous or somewhat toxic, and a short interval between pesticide applications and sales can put public health at risk. Many products have more than one active substance against the same disease. The time between the last spraying and harvesting of the licensed pesticides is hugely variable. This creates problems, especially in products with frequent harvesting processes, such as vegetables. In the current study, 95.7% of the participants stated that they respected the time between spraying, and 97.8% observed the time between the last spraying and harvest. These high compliance rates positively and significantly affected the farmers' residual risk perceptions. Contradictory findings were obtained in the literature. For example, none of the vegetable and fruit farmers in the north of the Delta, Egypt, followed the recommended pre-harvest no-spray interval [47]. More worryingly, 98% of Vietnamese farmers said they were aware of the pre-harvest interval but admitted that they did not always observe it [57].

Pest control must be carried out on a predetermined schedule. Waiting to observe pests and even damage before starting spraying increases residue risk. In the current study, half of the farmers (49.5%) sprayed after they observed pests or pest damage. Only 16.7% administered control strategies according to a predetermined schedule. Recent research presented consistent findings. Kuwaiti farm owners commonly applied pesticides when they observed pests or pest damage (40%), and 36% followed a predetermined schedule [34]. Pesticides are generally imported. Increases in exchange rates directly affect pesticide prices and constitute a substantial item in farmers' costs.

When dealers in Turkey were asked about the factors that farmers prioritize when selecting pesticides, the dealers stated that half of the farmers (51%) paid attention to the cheapness [56]. Consequently, almost all (90.1%) respondents used the recommended dose. Similarly, 87.5% of Lebanese farmers [58] and 82% of Algerian farmers claimed to always follow the recommended dose [59]. Although applying the pesticide at the recommended dose significantly reduces the likelihood of residue release, several pesticides are often mixed in practice. When farmers think the pesticide does not affect them, they prefer pesticides containing a more toxic active ingredient. More than two-thirds (67.8%) of Turkish farmers mixed several pesticides. When the pesticide was ineffective, 62.2% replaced it with a more toxic alternative, and 19.2% used more of the same pesticide. In the research conducted in West Java, Indonesia, 66.25% of the farmers mixed pesticides, and 50% carried this out because they believed the pesticides would be more effective [60].

Farmers claim that mixing chemicals saves time and labor. They also predict higher pest control efficiency. Mixing pesticides increases pest resistance and increases the risk of residues in foods. This study showed that applying pesticides by mixing increased the likelihood of residues in the products.

The research results from this study showed that as farmers were trained, their risk perception increased, and their perception of residue in the products increased. Thus, Hypothesis 4 was confirmed. Farmers' low education level is one of the most fundamental problems in farming practices. This gap can only be closed with dedicated training. Although cooperatives, various non-governmental organizations, and state institutions organize occasional training, it is seen from the research results that this training needs to be sufficient in quantity, and the participation needs to be higher. Less than a third (31%) of farmers in Turkey have received training. These results coincide with undeveloped countries; 31% of Ugandan farmers, 30% of Nepali farmers [25], and 33% of southwestern Nigerian farmers [46] had received pesticide training.

5. Conclusions and Future Directions

Excessive and inaccurate pesticide use in Turkey has had a detrimental effect on farmers' health and the environment, and it indirectly harms human health by resulting in intolerable residue levels. Numerous studies have investigated the inappropriate and excessive use of pesticides. However, only a handful of studies have examined farmers' knowledge of pesticide residues and focused on understanding the factors that influence their residue risk perceptions. The results of this study show that the farmers' overall pesticide risk perception was low. The results also show that farmer characteristics and pesticide application behaviors significantly positively affected pesticide residue risk perception. The pesticide purchase place, adherence to the period between the last spraying and the harvest, the dosage used, and membership in a cooperative were the factors that most affected the residual risk perceptions of the farmers.

Although the state provides fertilizer and diesel support to farmers, farmers need more support in the current economic climate in Turkey. The state should also add agricultural pesticide support to farmer support. The Ministry should regularly disclose the results of residue analyses for domestic consumption and make them available to universities, non-governmental organizations, and other organizations related to public health. The inspections carried out by the Ministry should be improved, and more food and agricultural engineers should be employed for this purpose.

The research results show that only a few members benefit from this training, but it is effective. This training within cooperatives should not only be limited to selecting and using pesticides but also include residue and health risks.

Pesticide dealers in Turkey are generally agricultural engineers. However, agricultural engineers are also trained primarily by vendor companies. The pesticide market is highly competitive. Pesticide retailers may lead farmers to choose pesticides with high profit margins for retailers, even though they are not effective in fighting targeted insects or diseases or their active ingredients are not allowed to be used in producing certain products. Therefore, dealers should be regularly trained and inspected by the relevant agricultural organizations rather than manufacturers.

There are many more information sources for farmers than before. Nevertheless, this information needs to be more cohesive. In addition, a large amount of data from different sources can be misleading. Improving public agricultural extension services to improve farmers' pesticide application behavior is essential. In Turkey, pesticide retailers have overtaken the agricultural extension system as the most prominent external information source on pesticide use for farmers. However, Turkey's agricultural extension services are not at the desired level, and farmers need to be made aware of independent agents. Therefore, increasing the visibility and effectiveness of extension agents is vital.

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References

1. Sener, S.; Turemis, N.F.; Tanir, F. Agrochemical usage for sustainable fruit production and human health. In *Agrochemicals Detection, Treatment and Remediation*; Prasad, M.N.V., Ed.; Butterworth-Heinemann: Oxford, UK, 2020; pp. 291–305.
2. Erdil, M.; Tiryaki, O. Investigaton of the knowledge level and awareness of farmers about pesticide usage in Manisa. *Çanakkale Onsekiz Mart Univ. J. Grad. Sch. Nat. Appl. Sci.* **2020**, *6*, 81–92. [CrossRef]
3. Gun, S.; Kann, M. Pesticide use in Turkish greenhouses: Health and environmental consciousness. *Pol. J. Environ. Stud.* **2009**, *18*, 607–615.
4. Pesticide Atlas 2022. In *Facts and Figures about Toxic Chemicals in Agriculture*; Heinrich-Böll-Stiftung, European Union: Brussels, Belgium, 2022. Available online: https://eu.boell.org/en/PesticideAtlas (accessed on 1 March 2024).
5. Gurbuz, I.B.; Abdullahı, A.M.; Ozkan, G. Integrated pest management practices in Somalia to reduce pesticide use in banana production. *Erwerbs-Obstbau* **2023**, *65*, 1793–1801. [CrossRef]
6. EFSA (European Food Safety Authority); Carrasco Cabrera, L.; Medina Pastor, P. The 2020 European Union report on pesticide residues in food. *EFSA J.* **2022**, *20*, e07215. [CrossRef] [PubMed]
7. Sade, G. *Civil Society in Turkey Came Together against Pesticides: Toxic-Free Tables Project*; Euronews: Lyon, France, 2020. Available online: https://tr.euronews.com/2020/02/19/turkiye-de-sivil-toplum-pestisite-karsi-bir-araya-geldi-zehirsiz-sofralar-projesi (accessed on 1 March 2024).
8. Karahan, S. Turkey's Food Security and GMO: Current Status and Future Strategies. MISAK-National Strategy Research Board. 2017. Available online: https://millidusunce.com/misak/turkiyenin-gida-guvenligi-ve-gdo-mevcut-durum-ve-gelecek-stratejileri/ (accessed on 1 March 2024).
9. Balci, H.; Durmusoglu, E. Biopesticides as plant protection products: A review of their definitions, classifications, legislation and markets. *Turk. J. Biol. Control.* **2020**, *11*, 261–274. [CrossRef]
10. Official Gazette, Licensing and Market Placement of Plant Protection Products Regulation No. 32489. 14 March 2024. Available online: https://www.resmigazete.gov.tr/eskiler/2024/03/20240314-5.htm (accessed on 1 March 2024).
11. Durmusoglu, E.; Tiryaki, O.; Kumral, N.A.; Aydin, A.; Gungor, O. Legislation on plant protection products, 47–72. In Proceedings of the Turkish Agricultural Engineering IX. Technical Congress, Ankara, Turkey, 13–17 January 2020. Proceedings Volume 2, TMMOB Chamber of Agricultural Engineers; 895p.
12. Official Gazette, Turkish Food Codex Regulation on Maximum Residue Limits of Pesticides. Regulation No. 29899. 25 November 2016. Available online: https://www.resmigazete.gov.tr/eskiler/2016/11/20161125M1-1.htm (accessed on 1 March 2024).
13. Hanedar, A.; Tanık, A.; Girgin, E. Pesticide management within the context of green deal and Turkiye. *ITU Environ. Clim. Sustain.* **2023**, *24*, 87–96.
14. Uysal, F.F.; Yildirim., C. Keskin, Management of empty pesticide containers in Turkey and in the World. In Proceedings of the 1st International Conference on Environment, Technology and Management ICETEM, Niğde, Turkey, 27–29 June 2019; pp. 204–210.
15. European Union. *2021 Annual Report, Alert and Cooperation Network*; European Union: Luxembourg, 2021.
16. Erberk, E.; Ozyoruk, A.; Arslan, U. Determination of attitudes and behaviors of fruit producers towards pesticide use in Gursu and Kestel districts of Bursa province. *J. Agric. Fac. Bursa Uludag Univ.* **2018**, *32*, 69–76.
17. Dilmen, H.; Pala, F.; Ozer Dilmen, M. Determination of knowledge level of pistachio (*Pistacia vera* L.) growers on agricultural pest control: The case of province Siirt, Turkey. *Turk. J. Agric. Res.* **2020**, *7*, 1–8. [CrossRef]
18. Gozener, B.; Sayili, M.; Caglar, A. Agricultural chemical use in tomato farming in Kazova region of Tokat province. *Turk. J. Agric. Food Sci. Technol.* **2017**, *5*, 451–458. [CrossRef]
19. Kowalik, R.; Widłak, M.; Widłak, A. Sorption of heavy metals by sewage sludge and its mixtures with soil from wastewater treatment plants operating in MBR and INR technology. *Membranes* **2021**, *11*, 706. [CrossRef]
20. Janaszek, A.; Kowalik, R. Analysis of heavy metal contaminants and mobility in sewage sludge-soil mixtures for sustainable agricultural practices. *Water* **2023**, *15*, 3992. [CrossRef]
21. Hou, B.; Wang, Z.-w.; Ying, R. Pesticide residues and wheat farmer's cognition: A China scenario. *Agric. Res.* **2016**, *5*, 51–63. [CrossRef]
22. Mehmood, Y.; Arshad, M.; Kaechele, H.; Mahmood, N.; Kong, R. Pesticide residues, health risks, and vegetable farmers' risk perceptions in Punjab, Pakistan. *Hum. Ecol. Risk Assess.* **2021**, *27*, 846–864. [CrossRef]
23. Wu, L.; Hou, B. China's farmer perception of pesticide residues and the impact factors. The case of Jiangsu province. *China Agric. Econ. Rev.* **2012**, *4*, 84–104. [CrossRef]
24. Bhandari, G.; Atreya, K.; Yang, X.; Fan, L.; Geissen, V. Factors affecting pesticide safety behavior: The perceptions of Nepalese farmers and retailers. *Sci. Total Environ.* **2018**, *631–632*, 1560–1571. [CrossRef] [PubMed]

25. Sun, S.; Hu, R.; Zhang, C. Pest control practices, information sources, and correct pesticide use: Evidence from rice production in China. *Ecol. Indic.* **2021**, *129*, 107895. [CrossRef]
26. Wang, C.; Liu, W. Farmers' attitudes vs government supervision: Which one has a more significant impact on farmers' pesticide use in China? *Int. J. Agric. Sustain.* **2021**, *19*, 213–226. [CrossRef]
27. Zhang, L.; Li, X.; Yu, J.; Yao, X. Toward cleaner production: What drives farmers to adopt eco-friendly agricultural production? *J. Clean. Prod.* **2018**, *184*, 550–558. [CrossRef]
28. Qin, S.; Lu, X. Do large-scale farmers use more pesticides? Empirical evidence from rice farmers in five Chinese provinces. *J. Integr. Agric.* **2020**, *19*, 590–599. [CrossRef]
29. Zhao, Q.; Pan, Y.; Xia, X. Internet can do help in the reduction of pesticide use by farmers: Evidence from rural China. *Environ. Sci. Pollut. Res.* **2021**, *28*, 2063–2073. [CrossRef]
30. Baharom, N.; Ali, J.; Aziz, F.S. Factors influencing intention to comply with the pesticide regulation among rice farmers. *Int. J. Soc. Sci. Humanit. Res.* **2018**, *6*, 101–107.
31. Karabat, S.; Atis, E. An analysis of effects on food safety of pesticide usages with contingent valuation method in Manisa vineyard areas. *J. Agric. Fac. Ege Univ.* **2012**, *49*, 17–25.
32. Zhao, L.; Wang, C.; Gu, H.; Yue, C. Market incentive, government regulation and the behavior of pesticide application of vegetable farmers in China. *Food Control* **2018**, *85*, 308–317. [CrossRef]
33. Zhu, W.; Wang, R. Impact of farm size on intensity of pesticide use: Evidence from China. *Sci. Total Environ.* **2021**, *753*, 141696. [CrossRef]
34. Jallow, M.F.; Awadh, D.G.; Albaho, M.S.; Devi, V.Y.; Thomas, B.M. Pesticide risk behaviors and factors influencing pesticide use among farmers in Kuwait. *Sci. Total Environ.* **2017**, *574*, 490–498. [CrossRef]
35. Jin, S.; Bluemling, B.; Mol, A.P. Information, trust and pesticide overuse: Interactions between retailers and cotton farmers in China. *NJAS Wagening. J. Life Sci.* **2015**, *72-73*, 23–32. [CrossRef]
36. Migheli, M. Land ownership and use of pesticides. Evidence from the Mekong Delta. *J. Clean. Prod.* **2017**, *145*, 188–198. [CrossRef]
37. Uzundumlu, A.S.; Kilic, B.; Tozlu, G. Analysis of factors affecting pesticide use in hazelnut production: The case study of Giresun. *Gumushane Univ. J. Sci. Technol.* **2017**, *7*, 1–9. [CrossRef]
38. Camur, D.; Vaizoglu, S.A.; Guler, Ç. Are pesticide applicators in Turkey able to protect themselves? *Cukurova Med. J.* **2017**, *42*, 254–263. [CrossRef]
39. Jin, J.; Wang, W.; He, R.; Gong, H. Pesticide use and risk perceptions among small-scale farmers in Anqiu County, China. *Int. J. Environ. Res. Public Health* **2017**, *14*, 29. [CrossRef]
40. U.I.B. *Fresh Fruit and Vegetable Sector Report*; Uludag Exporters Union: Bursa, Turkey, 2019. Available online: https://uib.org.tr/tr/kbfile/yas-meyve-sebze-sektor-raporu (accessed on 1 March 2024).
41. Benson, M.L.; Levine, D.M.; Krehbiel, T.C. *Basic Business Statistics: Concepts and Applications*, 8th ed.; Prentice Hall: Hoboken, NJ, USA, 2002.
42. Park, H.-A. An introduction to logistic regression: From basic concepts to interpretation with particular attention to nursing domain. *J. Korean Acad. Nurs.* **2013**, *43*, 154–164. [CrossRef]
43. Fernihough, A. Simple Logit and Probit Marginal Effects. In *R. Working Papers 2011*; School of Economics, University College Dublin: Dublin, Ireland, 2011.
44. Sapbamrer, R.; Thammachai, A. Factors affecting use of personal protective equipment and pesticide safety practices: A systematic review. *Environ. Res.* **2020**, *185*, 109444. [CrossRef]
45. Garrigou, A.; Laurent, C.; Berthet, A.; Colosio, C.; Jas, N.; Daubas-Letourneux, V.; Judon, N. Critical review of the role of P.P.E. in the prevention of risks related to agricultural pesticide use. *Saf. Sci.* **2020**, *123*, 104527. [CrossRef]
46. Sosan, M.B.; Akingbohungbe, A.E. Occupational insecticide exposure and perception of safety measures among Cacao farmers in Southwestern Nigeria. Arch. of Environ. *Occup. Health* **2009**, *64*, 185–193. [CrossRef]
47. Abbassy, M.M. Farmer's knowledge, attitudes and practices, and their exposure to pesticide residues after application on the vegetable and fruit crops. Case study: North of Delta, Egypt. *J. Environ. Anal. Toxicol.* **2017**, *7*, 1–6. [CrossRef]
48. Tandi, T.E.; Wook, C.J.; Shendeh, T.T.; Eko, E.A.; Afoh, C.O. Small-scale tomato cultivators' perception of pesticide usage and practices in Buea Cameroon. *Health* **2014**, *6*, 2945–2958. [CrossRef]
49. Al Zadjali, S.; Morse, S.; Chenoweth, J.; Deadman, M. Factors determining pesticide use practices by farmers in the Sultanate of Oman. *Sci. Total Environ.* **2014**, *476–477*, 505–512. [CrossRef]
50. Ibitayo, O.O. Egyptian farmers' attitudes and behaviors regarding agricultural pesticides: Implications for pesticide risk communication. *Risk Anal.* **2006**, *26*, 989–995. [CrossRef]
51. Sharafi, K.; Pirsaheb, M.; Maleki, S.; Arfaeinia, H.; Karimyan, K.; Moradi, M.; Safari, Y. Knowledge, attitude and practices of farmers about pesticide use, risks, and wastes; a cross-sectional study (Kermanshah, Iran). *Sci. Total Environ.* **2018**, *645*, 509–517. [CrossRef]
52. Yang, X.; Wang, F.; Meng, L.; Zhang, W.; Fan, L.; Geissen, V.; Ritsema, C.J. Farmer and retailer knowledge and awareness of the risks from pesticide use: A case study in the Wei River Catchment, China. *Sci. Total Environ.* **2014**, *497–498*, 172–179. [CrossRef]
53. Tezcan, H.; Ozahiskali, H.; Toktay, S.; Gunaltay, S.; Kilinc, I.; Akbas, L.; Yildirim, I. Changes in education and education of agricultural pharmaceutical dealers. In Proceedings of the Agricultural Engineering VII. Technical Congress, Ankara, Turkiye, 1–4 January 2010; pp. 645–650.

54. Jean, S.; Emmanuel, F.; Edouard, A.N. Brownlinda, Farmers' knowledge, attitude and practices on pesticide safety: A case study of vegetable farmers in Mount-Bamboutos agricultural area, Cameroon. *Agric. Sci.* **2019**, *10*, 1039–1055. [CrossRef]
55. Satya Sai, M.V.; Revati, G.D.; Ramya, R.; Swaroop, A.M.; Maheswari, E.; Kumar, M.M. Knowledge and perception of farmers regarding pesticide usage in a rural farming village, Southern India. *Indian J. Occup. Environ. Med.* **2019**, *23*, 32–36. [CrossRef] [PubMed]
56. Saglam Altinkoy, H.D.; Akan, K.; Kan, A.; Korkmaz, A. Evaluation of plant protection products dealers' current situation and their problems in Kirsehir province. *Mediterr. Agric. Sci.* **2020**, *33*, 351–359. [CrossRef]
57. Nguyen, M.T.; Le, N.T.; Havukainen, J.; Hannaway, D. Pesticide use in vegetable production: A survey of Vietnamese farmers' knowledge. *Plant Prot. Sci.* **2017**, *54*, 203–214. [CrossRef]
58. Mardigian, P.; Chalak, A.; Fares, S.; Parpia, A.; El Asmar, K.; Habib, R.R. Pesticide practices in coastal agricultural farms of Lebanon. *Int. J. Environ. Health Res.* **2021**, *31*, 132–147. [CrossRef]
59. Soudani, N.; Belhamra, M.; Toumi, K. Pesticide use and risk perceptions for human health and the environment: A case study of Algerian farmers. *Ponte* **2020**, *76*, 10–28. [CrossRef]
60. Munif, A.; Rachmawati, V. Knowledge, attitude and action of farmers in controlling plant pest and disease of potato in Garut, West Java. In Proceedings of the Southeast Asia Plant Protection Conference, Bogor, Indonesia, 14 August 2019; Volume 468, p. 012053.

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Exploring the Mechanisms of Regional Environmental Collaborative Legislation in China: Policy Effectiveness, Practical Challenges, and Policy Suggestions

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Abstract: The legislation for regional environmental collaboration is of significant importance in enhancing the effectiveness of environmental protection. The existing literature focuses on the power struggle between central and local governments regarding environmental regulation within the realm of regional environmental governance, lacking an examination of the collaborative governance mechanisms and their effectiveness. Therefore, this study takes China's regional environmental collaborative legislation as its research object. It employs a difference-in-differences model to test the effectiveness of regional environmental collaborative legislation concerning environmental governance and conducts a qualitative analysis to examine the current practical challenges facing regional environmental collaborative legislation. The quantitative analysis results indicate that regional environmental collaborative legislation can effectively suppress the emission of environmental pollutants. Specifically, the implementation of regional environmental collaborative legislation results in a 19.7% reduction in prefecture-level wastewater emissions and a 26.6% reduction in sulfur dioxide emissions. Qualitative analysis results show that regional environmental collaborative legislation currently faces challenges such as localism, difficulties in legislative authority allocation, and a lack of cooperation mechanisms. Therefore, this paper proposes to establish a collaboration platform, balance the interests of stakeholders, and improve the allocation mechanism of environmental regulatory powers in order to better optimize the regional environmental collaborative legislation and enhance the government's environmental governance capacity.

Keywords: regional environmental collaborative legislation; environmental pollution; environmental legislation; environmental protection

1. Introduction

China's economy has transitioned from a phase of high-speed growth to a stage of high-quality development, a shift highlighted in the report of the 20th National Congress of the Communist Party of China. This report emphasizes the critical role of greening and low-carbon development in achieving high-quality growth, thereby delineating a future direction for both environmental governance and economic development. This necessitates a stronger emphasis on regional environmental governance to stimulate industrial restructuring, promote a positive economic cycle, and garner additional financial and technical support for environmental management efforts. In this context, the Chinese government and its associated departments have prioritized the construction of a social ecological civilization, encapsulating this commitment with the slogan, "Building an ecological civilization is essential for the people's wellbeing and the nation's future". This has spurred explorations in governance models for regional and local environmental protection at both central and local government levels.

From a global perspective, regional environmental issues are common challenges faced by the international community. Globally, there are two collaborative governance

models based on different political systems for regional environmental governance. One is the environmental federalism governance model, led by federal states, and the other is the regional environmental collaborative legislative model, led by unitary states [1]. The political system has a particularly significant impact on the collaborative governance model. For instance, the United States' federal system brings about environmental federalism in environmental governance, with the power struggle between the federal government and state governments being at the core of environmental federalism [2]. The federal government and state governments in the United States have been in contention over the interpretative authority regarding "waters of the United States" under the Clean Water Act [3]. The competition between central and local governments can also lead local governments to strengthen the overall environmental governance capacity of the country through local initiatives. The multi-level governance (MLG) formed by the European Union and its member states in regards to global climate and energy governance is a typical example [4]. Germany, a federal state and a pioneer representative of the European Union, has seen more than 140 municipal governments formulate the goal of obtaining 100% of their electricity from renewable sources. This initiative has led to 30% of the country becoming powered entirely by renewable energy [5].

However, in the complex realm of regional environmental governance, particularly concerning air pollution and river management, the power struggle between central and local governments under environmental federalism, along with the limited effectiveness of individual local initiatives in addressing cross-regional environmental issues, has underscored the increasing importance of local and regional cooperation. In the realm of air pollution governance, although the US Congress enacted the 1970 Clean Air Amendments, requiring the attainment of uniform air quality standards, this goal was ultimately not achieved due to the differences in implementation by local governments in environmental governance decision making [6]. In river management, local governments in unitary states are more likely to form river partnerships based on the overall objectives of national environmental regulation. For instance, the Catchment Based Approach (CaBA), initiated in 2013 by the UK Government, employs a collaborative approach to water management throughout England. Over the six years since its inception, there have been 106 river catchment partnerships established [7]. Japan, another unitary state in East Asia, has also adopted inter-municipal cooperation (IMC) for regional waste management [8]. As the largest unitary state, the relationship between the central government and local governments in China is one of leadership and being led. Therefore, the power struggle between the central government and local governments is not the core issue in regional environmental governance. The governance model adopted by the Chinese government for regional environmental issues is regional environmental collaborative legislation. This governance model mainly focuses on cooperation and conflict among local governments, rather than on the power struggle between the central government and local governments.

This study focuses on China, the largest unitary state, to investigate its adoption of the regional environmental collaborative legislation in addressing regional environmental issues. This approach is not only based on global governance practices in response to regional environmental issues, but it also seeks to fill the research gap regarding the participation of unitary states in regional environmental governance. The research questions addressed in this study are as follows: Is the regional environmental collaborative legislation adopted by China effective in addressing regional environmental issues? What are the current practical challenges facing existing regional environmental collaborative legislation? How should the regional environmental collaborative legislative model be optimized in the future to enhance environmental governance capabilities? Therefore, this research aims to evaluate the effectiveness of the regional environmental collaborative legislation through qualitative research and to examine the practical challenges of this model through normative analysis, providing valuable institutional recommendations.

The regional environmental collaborative legislation aims to address the public, dynamic, and holistic nature of environmental challenges, with a specific focus on cross-

regional governance [9]. This approach emphasizes breaking down administrative and interest-based barriers, fostering an integrated and synergistic approach to regional environmental law. This form of legislation addresses the issue of fragmentation in environmental regulations formulated by individual regions, thereby enhancing the overall effectiveness of environmental protection. It has gradually gained attention and application from both central and local governments. Guided by the principles of legislation for regional environmental collaboration, China's environmental legislation philosophy is becoming more coherent, its legal frameworks are continually being refined, and governance institutions are being optimized, leading to significant improvements in environmental management [10]. However, regional environmental collaborative legislation may still face the following challenges: firstly, the gap caused by regional disparities in political status, economic development, geographical conditions, and cultural traditions; secondly, whether regional environmental collaborative legislation can mobilize the governance role of multi-level local legislative entities across regions; thirdly, conflicts and coordination issues between regional environmental collaborative legislation and local environmental legislation.

In the introductory context of regional environmental governance, the scholarly discourse reflects a significant interest in and response from both theoretical and practical domains.

Firstly, a substantial volume of literature has delved into the necessity of regional environmental collaborative legislation. Briffault (2000) posits that regionalism, as a theory opposed to localism, suggests that future societal governance should shift from localism to regionalism. He further notes that the application of regional policies can effectively address issues of regional environmental protection [11]. Meng (2016) specifically examines the Beijing—Tianjin—Hebei region, advocating for the enhancement of local environmental collaborative legislation and the establishment of a regional environmental legal framework. This approach is seen as vital for providing strong legal backing to jointly improve the regional ecological environment [12]. Wang (2018) extends this discussion by arguing that regional environmental legislation is a critical requirement for the integrated economic development of regions. Wang emphasizes the role of legal measures in balancing rights and interests and in upholding stability and development within regional economies [13]. Furthermore, Huang and Li (2023) contribute to this discourse by asserting that regional environmental legislation, steered through laws, not only guides regional environmental law enforcement cooperation but also lays the groundwork for judicial coordination within the region. They contend that such legislative initiatives enhance the environmental protection consciousness of governments, businesses, and the public, thereby augmenting the regional capability for environmental rule of law and consequentially, improving the regional environmental quality [14].

Secondly, several scholars have also elucidated regional environmental collaborative legislation from a practical perspective, focusing on its models, mechanisms, and systems. Yang and Qiu (2016) suggest that the top-level design of regional environmental collaborative legislation models should incorporate the concept of fiscal cooperation [15]. Wang and Wang (2016), beginning with the environmental governance issues in the Beijing—Tianjin—Hebei region, analyze the necessity of regional environmental collaborative legislation. They summarize the current status of multi-centric governance and environmental collaborative legislation theories and practices, proposing a model based on "four centers", consisting of government, businesses, the public, and non-governmental environmental organizations [16]. Si and Zhang (2021) present three distinct types of legislation models based on dynamic mechanisms: the "hierarchical authority" model, exemplified by the Beijing—Tianjin—Hebei region, the "inter-governmental consultation" model, represented by the Yangtze River Delta, and the "campaign-style" model, illustrated by the Fen-Wei Plain area [17]. Chen (2023) views the regional environmental collaborative legislation system as a cyclic system integrating "causes, agents, dynamics, actions, and outcomes". This study describes the legislation mechanism as an organic system comprising organizational, dynamic, operational, feedback, and interactive mechanisms [18].

Thirdly, emerging literature has begun to increasingly focus on the impact of regional environmental collaborative legislation on environmental governance, discussing its effects through both qualitative and quantitative analyses. In terms of qualitative analysis, Zhou (2020) explores the improvement directions of regional environmental collaborative legislation from aspects like models, dynamics, and pathways, emphasizing the significance of intergovernmental cooperation under China's decentralized system for environmental governance [19]. Suo and Li (2021) analyze the structural attributes and evolutionary characteristics of regional environmental collaborative governance from a perspective of multi-entity co-governance, constructing an environmental governance framework under regional environmental collaborative legislation [20]. In the realm of quantitative analysis, Han (2017) employs the bootstrap-DEA model to assess the efficiency of China's ecological environment collaborative governance [21]. The study discovers significant regional disparities in China's environmental collaborative governance, which exhibit a U-shaped characteristic of initial convergence, followed by divergence. Zhang and Shang (2018) utilize a coupling assessment model to evaluate the green development collaborative performance in the Yangtze River Delta and the ecological environmental collaborative governance performance of 45 cities in Western China [22]. Their findings reveal a strong pollution reduction effect of regional environmental collaboration and explore differentiated pathways for the practical implementation of regional environmental collaborative legislation to promote pollution reduction.

Overall, the existing research has predominantly focused on explicating and analyzing the concepts and mechanisms of regional environmental collaborative legislation, often adopting a relatively singular perspective. However, the issue of regional environmental collaborative governance cannot be thoroughly understood through a singular lens; it demands a profound grasp of its fundamental problems. The reviewed studies lack a focused examination of the research question, centering primarily on the issues related to regional environmental collaborative legislation. As an important legislative type, regional environmental collaborative legislation exhibits distinct characteristics in regards to policy effects, practical dilemmas, and systemic optimization. Moreover, the existing literature tends to employ basic research methods to discuss the environmental governance effects of regional environmental collaborative legislation, lacking sufficient and effective empirical evidence, particularly from a quantitative analysis standpoint. Building upon the foundation of the existing literature, this paper explores the normative documents and governance outcomes of regional environmental governance. It employs a difference-in-differences model to empirically test the policy effects of regional environmental collaborative legislation, aiming to explore the causal relationship between norms and governance outcomes. Further, to avoid turning regional environmental governance into an "ivory tower" concept, this paper investigates the governance effectiveness and practical manifestations of regional environmental collaborative legislative mechanisms under the guidance of legislative texts. Based on this, it proposes pathways to enhance the regional environmental collaborative legislative mechanism. This has significant practical implications for promoting the high-quality integrated development of regional economies and societies.

To examine the effectiveness of regional environmental collaborative legislation in regards to environmental governance and to analyze its practical challenges, this paper first meticulously sorts out the legislative documents concerning regional environmental collaboration in three major Chinese regions: the Three Northeastern Provinces, the Yangtze River Delta region, and the Beijing—Tianjin—Hebei region. It provides a comprehensive analysis and discussion of the legislative models and distinctive features of regional environmental collaboration in these areas. Building on this, the study utilizes prefecture-level data from China spanning 2010 to 2019 to construct a difference-in-differences model (DID). This model empirically tests the policy impact of regional environmental collaborative legislation on prefecture's environmental pollution. In conjunction with the current state of regional environmental collaborative legislation in these three regions, the paper delves into the practical challenges and optimization paths inherent in implementing this

legislation. The findings of the study indicate that regional environmental collaborative legislation effectively reduces urban environmental pollution levels in the collaborative regions, significantly demonstrating its efficacy in environmental governance. However, the current practice of regional environmental collaborative legislation in these areas faces challenges, including severe local profit-seeking, a unidimensional legislative hierarchy, and insufficient collaborative mechanisms. Therefore, the paper suggests the need to establish cross-regional environmental protection cooperation mechanisms and negotiation platforms, while also improving the horizontal collaboration mechanisms and vertical delegation mechanisms for regional environmental legislation. Through both internal and external drivers, this optimization and transformation of regional environmental governance can be achieved, providing essential institutional support for regional environmental legislative cooperation.

2. Institutional Background: The Practical Characteristics of Regional Environmental Collaborative Legislation Mechanisms

The mechanism of regional environmental collaborative legislation, which emphasizes inter-local cooperation rather than the division of power between central and local governments, reflects the reality of the new regionalism theory in environmental governance strategies. The new regionalism theory suggests that neither localism, advocating for local autonomy, nor the regional general-purpose governments proposed by old regionalism theories, are the most effective ways to address regional environmental issues. Instead, voluntary collaboration across regions is seen as the future trend [23]. Therefore, before evaluating the impact of regional environmental collaborative legislation on environmental governance, it is essential to examine the diverse models of "voluntary collaboration" within regional environmental collaborative legislation.

The model of regional environmental collaborative legislation in China did not emerge solely as a result of explicit provisions in the legislative law. Drawing on the country's traditional "pilot policy" approach, the Three Northeastern Provinces had already initiated the precedent for regional collaborative legislation in 2006 [24], with the Yangtze River Delta region following suit in 2007, developing a unique collaborative legislative model. Although the collaborative legislation in the Beijing—Tianjin—Hebei region, centered around Beijing, was developed later, it also presented a distinctive model of cooperation. Thus, it is imperative to first trace the historical trajectory of these three collaborative legislative models. After analyzing the specific frameworks of each model individually, an abstracted analysis focusing on the regional environmental collaborative legislative model itself should be conducted [12].

With the decision to amend the Legislation Law passed by the 14th National People's Congress in 2023, regional collaborative legislation was officially recognized for its legal status and effectiveness. However, Article 83 of the Legislation Law merely states that "provinces, autonomous regions, municipalities directly under the Central Government, and cities with districts, autonomous prefectures may establish mechanisms for regional collaborative legislative work", without detailing the practical models of such legislation. Therefore, it is necessary to analyze the existing practices of regional environmental collaborative legislation prior to this amendment. Based on the "pilot policy" initiatives already in place, this analysis aims to anticipate a collaborative model that aligns with the amendments to the Legislation Law [25].

2.1. Regional Collaborative Legislation in the Three Northeastern Provinces: A Semi-Intensive Legislative Model

The Three Northeast Provinces specifically refer to the three provinces in the northeastern part of China: Heilongjiang, Jilin, and Liaoning. (Refer to the yellow area in Figure 1 for details) According to the latest data, the population of the urban agglomeration in the Three Northeast Provinces has reached 98.51 million, and the GDP total reached CNY 5.96 trillion in 2023, making it the most densely populated region of resource-based cities in China. As China's old industrial base, the Northeast region has made remarkable contributions

to China's socio-economic development by vigorously developing heavy chemical and resource-based industries based on the mineral resources in the region.



Figure 1. The geographical positioning of the Three Northeast Provinces, the Yangtze-River Delta region, and the Beijing—Tianjin—Hebei region in China.

Drawing on China's tradition of "pilot policies", these provinces initiated a pioneering regional legislative collaboration framework as early as 2006, with the signing of the "Three Northeast Provinces Governmental Legislative Collaboration Framework Agreement". This framework introduced a three-tiered model of legislative collaboration—intensive, semi-intensive, and dispersed—among which the Three Northeast Provinces adopted a semi-intensive model. This model entails one province taking the lead in drafting legislation on issues of mutual concern, with the other two providing support throughout the process. Given the absence of statutory provisions for regional collaborative legislation at the time, the framework explicitly designated provincial governments as the legislative bodies, confining the level of legislation to provincial government regulations and adopting a relatively uniform legislative model. The initial batch of nine legislative collaboration projects all followed the semi-intensive model, without any specific plans for environmental legislation.

Firstly, in terms of legislative subjects, as the concepts of ecological protection and environmental governance gain widespread acceptance, the Three Northeast Provinces have progressively developed specialized legislation aimed at protecting specific natural areas, such as the Songhua River Basin, black soil lands, and wetlands, prioritizing natural regions or elements for targeted protection. Examples include watershed environmental legislation (Heilongjiang Province, Jilin Province: "Songhua River Basin Water Pollution Prevention Regulations"), soil environmental legislation (Heilongjiang Province, Jilin Province: "Black Soil Land Protection Regulations"), and wetland environmental legislation (Heilongjiang Province, Jilin Province, Liaoning Province: "Wetland Protection Regulations"). These laws are characterized by identifying unique conservation targets within administrative regions, predominantly adopting the semi-intensive legislative model and providing guidance for administrative law.

Secondly, there is a lack of uniformity in the levels of legislation. Although the collaborative legislation in the Three Northeast Provinces is based on a governmental legislative collaboration framework agreement, the practice of establishing legal norms is not confined to local government regulations. Some manifest as local regulations enacted by the Local People's Congresses, acting as the legislative bodies, while others are normative documents of a lower efficacy level, or administrative agreements without external legal force.

Thirdly, the phenomenon of non-collaborative local environmental legislation exists within environmental legislative collaboration. For instance, the "Songhua River Basin

Water Pollution Prevention Regulations", implemented by Heilongjiang and Jilin provinces, despite their similar timing and content, were enacted independently, with Jilin's legislation preceding that of Heilongjiang. The legislation enacted by Heilongjiang Province aimed, in part, to align with Jilin Province's legislation. While seemingly collaborative in form, both essentially constitute "local environmental legislation".

Lastly, the aim of collaborative legislation is to guide collaborative enforcement to spur economic growth. This is manifested in the cooperation and division of responsibilities among administrative agencies, refining the content of administrative law enforcement [26], without substantively legislating the collaborative aspect. The initial purpose of establishing a framework for regional collaborative legislation among the Three Northeast Provinces was to facilitate legislative alignment and enforcement uniformity across the provinces, thereby revitalizing the industrial base of the Northeast and achieving significant economic development. Economic growth remained a common goal of regional collaborative legislation for a considerable period thereafter.

2.2. Regional Collaborative Legislation in the Yangtze River Delta: An Intensive Legislative Model

The Yangtze River Delta region is located in the downstream area of the Yangtze River in China, mainly including the provinces of Zhejiang, Jiangsu, and Anhui, as well as the municipality of Shanghai (refer to the orange area in Figure 1 for details). According to the latest data, the population of the urban agglomeration in the Yangtze River Delta has reached 235 million, and the GDP total reached CNY 30.50 trillion in 2023, making it one of the most active, open, and innovative regions regarding China's economic development. The Yangtze River Delta region serves as an important platform for China's participation in international competition, a vital engine for economic and social development, and a leader in the Yangtze River Economic Belt.

Its regional collaborative legislation includes the "Minutes of the Suzhou-Zhejiang-Shanghai Legal Cooperation Symposium". Similar to the Three Northeast Provinces, the primary goal of legislative collaboration in the Yangtze River Delta was also to promote economic growth, encouraging economic collaboration, oppose local protectionism, and unify law enforcement efforts. Unlike the Three Northeast Provinces, where collaborative legislation began with the signing of administrative agreements, the aforementioned minutes only provided guiding principles and legislative concepts for collaboration, without establishing a specific legislative model or working mechanism. Moreover, since the minutes were jointly signed by the Legal Affairs Committees of the People's Congresses, Government Legal Affairs Offices, and Law Societies of Jiangsu, Zhejiang, and Shanghai, their nature was not consistent with that of practical administrative agreements.

Scholars have categorized the collaborative legislative models in the Yangtze River Delta into "intensive, semi-intensive, and dispersed" types. Based on its collaborative characteristics, the region's collaborative legislative model is primarily considered intensive. In practice, the Yangtze River Delta has developed various supporting mechanisms, such as legislative planning and collaboration mechanisms, information sharing mechanisms, and media cooperation mechanisms, gradually aligning closer to an intensive legislative model.

Since the 18th National Congress of the Chinese Communist Party, the Central Committee and the State Council have placed great emphasis on the construction of a social ecological civilization. The Yangtze River Delta has achieved fruitful outcomes in ecological and environmental legislative collaboration, mainly represented by two types, which are discussed below.

The first type is regional environmental collaborative legislation based on administrative regions, exemplified by the "Regulations on the Prevention and Control of Air Pollution". The "Shanghai Municipal Regulations on the Prevention and Control of Air Pollution" includes a chapter on "Collaboration on Air Pollution Prevention and Control in the Yangtze River Delta". Subsequent amendments or enactments of the "Zhejiang Provincial Regulations on the Prevention and Control of Air Pollution" and the "Jiangsu Provincial Regulations on the Prevention and Control of Air Pollution" all specify "Regional

Joint Prevention and Control of Air Pollution", with consistent content across the three jurisdictions, detailing information sharing, joint research, policy unification, and joint enforcement among other provinces and municipalities. While specifying collaborative legislation in a dedicated chapter, these regulations largely preserve the autonomy of each province or municipality in other provisions.

The second type is based on natural regions, which are also an integral part of local regulations. This category is further divided into two modes: "Decisions on Promoting and Ensuring the Construction of the Demonstration Zone for Ecological and Green Integrated Development in the Yangtze River Delta" and "Decisions on Promoting and Ensuring the Work on Fishing Bans in the Yangtze River Basin" by various provinces and municipalities. The former represents narrow regional environmental collaborative legislation, where the Standing Committees of the People's Congresses in Jiangsu, Zhejiang, and Shanghai, after closely consulting and exchanging views, simultaneously issued regulations with identical content, providing comprehensive and directive guidance. The latter, led by Shanghai, and after soliciting written opinions from Jiangsu and Zhejiang, further unifies specific issues, with slightly different content in local regulations, representing broad regional environmental collaborative legislation.

2.3. Regional Collaborative Legislation in the Beijing—Tianjin—Hebei Area: A Dispersed Legislative Model

The Beijing—Tianjin—Hebei region, located in northern China, primarily includes Beijing, Tianjin, and Hebei (refer to the red area in Figure 1 for details). According to the latest data, the population of the Beijing—Tianjin—Hebei urban agglomeration has reached 114 million, with a GDP total of CNY 10.4 trillion in 2023, making it the most economically developed region in northern China. The Beijing—Tianjin—Hebei region serves as a vital economic hub and a world-class metropolitan area, playing a crucial role in China's overall spatial development and regional coordinated development framework.

The inception of collaborative legislation in the Beijing—Tianjin—Hebei region can be traced back to the issuance of the "Opinions on Strengthening the Collaborative Legislation of People's Congresses in the Beijing—Tianjin—Hebei region" in 2015. In accordance with the typology system previously discussed, which categorizes collaborative legislative models based on the degree of collaboration, the environmental collaborative legislation in the Beijing—Tianjin—Hebei region falls under the category of a "dispersed model". This model differs significantly from the collaborative legislation models observed in the Yangtze River Delta and the Three Northeast Provinces. In the Yangtze River Delta and the Three Northeast Provinces regions, the legislative model is characterized by being "collaborative and consistent," whereas in the Beijing—Tianjin—Hebei region, a "dispersed legislative model" prevails, resulting in a "collaborative but inconsistent" situation. This leads to what is often referred to as the "layered model" in the Beijing—Tianjin—Hebei region, with distinct legislative initiatives in Beijing, Tianjin, and Hebei.

Firstly, in terms of priority areas, the Beijing—Tianjin—Hebei region prioritizes infrastructure development and environmental protection, distinct from the Yangtze River Delta and Three Northeast Provinces, which prioritize economic growth and rapid development.

Secondly, regarding safeguard mechanisms, the Beijing—Tianjin—Hebei region's local collaborative legislation has established safeguard mechanisms with organizational significance. This uniqueness can be attributed to the divergent development focuses and layered positioning among Beijing, Tianjin, and Hebei. Scholars have found through empirical testing that there are significant developmental disparities in the Beijing—Tianjin—Hebei region, and the three sub-regions have not yet entered a stage of coordinated development [27]. As outlined in the "Outline of the Beijing—Tianjin—Hebei Collaborative Development Plan", Beijing serves as the political and cultural center of China, making it the core region for collaborative legislation. Tianjin leads in emerging industries, serving as a key area for legislative focus. Meanwhile, Hebei operates as an experimental zone for industrial upgrading, ensuring legislative support [28].

While the Beijing—Tianjin—Hebei region adopts a dispersed legislative model, the practical results of legislation are quite the opposite. Despite significant differences in the specific content of environmental collaborative legislation due to the diverse focuses and layered relations, the collaborative legislation achieves synergy in legal enforcement practices after enactment, effectively fulfilling its legislative objectives and intended outcomes [29]. This form of incongruence in structure but congruence in essence characterizes the collaborative model in the Beijing—Tianjin—Hebei region. The differentiation in collaborative legislation is most evident in the variations among the Beijing—Tianjin—Hebei region's "Regulations on the Prevention and Control of Atmospheric Pollution". Specifically, the legislation in Beijing is the most stringent, allowing for the formulation of local standards which are stricter than the national standards. Tianjin adopts a moderately strict approach, permitting the establishment of more stringent local standards, if no national standards exist. Hebei follows a relatively lenient path, requiring a deadline compliance when national standards are not met and aligning its standards closely with those of Tianjin. Additionally, the identification of polluting activities subject to penalties varies among the three regions. For instance, both Beijing and Tianjin prohibit outdoor burning of materials, such as asphalt, that pollute the atmosphere. Meanwhile, Hebei prohibits such activities in densely populated areas and other areas requiring special protection. Furthermore, the determination of penalty amounts displays discrepancies. Although all three regions set similar lower and upper limits for penalties related to unlawful activities, Beijing and Tianjin exercise more discretion in evaluating the severity of violations, while Hebei relies on the seriousness of the offense to determine penalty amounts.

The legislative phenomena mentioned above indicate that environmental legislation on atmospheric pollution in Beijing and Tianjin will be more stringently implemented here than in Hebei. This legislative diversity stands in contrast to the efforts in the Yangtze River Delta and the Three Northeast Provinces, where a consistent legislative model is pursued. This "dispersed legislative model" facilitates the gradual relocation of heavily polluting enterprises from Beijing and Tianjin to Hebei due to the more lenient local legislation. Subsequently, these enterprises leverage Hebei's legislative framework to achieve industrial upgrading, contributing to the phased ecological protection of the Beijing—Tianjin—Hebei region.

3. Empirical Examination of the Policy Effects of Regional Environmental Collaborative Legislation

3.1. Data and Methodology

3.1.1. Data and Sample

The database used in this paper comes from the China City Statistical Yearbook, published by the National Bureau of Statistics of China, which comprehensively reports the socioeconomic development and urban construction of each prefecture-level city in China. We collected the prefecture-level pollution emissions, as well as the prefecture-level control variables, from the China City Statistical Yearbook. In addition, the relevant documents for regional environmental collaborative legislation come from the official website of the Chinese People's Congress deputies and local government portals. We obtained the corresponding legislative documents through manual collection. Based on the above datasets, we finally construct balanced panel of data composed of environmental pollution emissions and legislative documents from a total of 299 prefecture-level cities from 2010 to 2019 for analysis.

3.1.2. Identification Strategy

To examine the casual relationship between regional environmental collaborative legislation and prefecture -level pollution emissions, we estimate the following specification, using the difference-in-differences model:

$$Pollution_{ict} = \alpha + \beta Treat_c \times Post_t + X'_{it}\gamma + \lambda_i + \lambda_t + \varepsilon_{ict} \quad (1)$$

where $Pollution_{ict}$ denotes environmental pollution emissions for prefecture i in province c at year t. $Treat_c$ is a dummy variable that indicates the prefecture i in province c, which carries out regional environmental collaborative legislation. $Post_t$ is a dummy variable, before and after the establishment of regional environmental collaborative legislation, taking the value of one after the legislation and onwards and zero otherwise. X_{it} is a vector of time-varying prefecture-level control variables. In addition, we introduce prefecture-specific and year-specific fixed effects in the model equation to capture factors that alter at the prefecture- and year-level. ε_{ict} is an idiosyncratic error term, controlling for other unspecified factors. We focus on the coefficient β of DID term $Treat \times Post$, which examines the causal effect of regional environmental collaborative legislation on prefecture-level pollution emissions.

3.1.3. Variable Measurement

Measurement of regional environmental collaborative legislation. A key issue in this paper is the measurement of regional environmental collaborative legislation. We manually collected regional environmental collaborative legislation documents from 2010 to 2019 in the Three Northeast Provinces, the Yangtze River Delta Region, and the Beijing—Tianjin—Hebei region from official website. Specifically, if a prefecture-level city in the above three regions proposes relevant legislative documents for regional environmental collaborative legislation, we regard it as a city carrying out regional environmental collaborative legislation, which provides important support for our subsequent identification of treatment groups and control groups. Through manual collection and identification, we determine that the research sample used in this paper includes a total of 64 prefecture-level cities that carry out regional environmental collaborative legislation (we call this the treatment group) and 235 prefecture-level cities that do not carry out collaborative legislation (i.e., the control group).

Measurement of pollution emissions. Using data from the China City Statistical Yearbook, we employ several pollutants to gauge prefecture-level pollution emissions. The China City Statistical Yearbook reports several types of pollution indicators at the prefecture level, such as wastewater emissions, flue gas, soot, and sulfur dioxide emissions (SO_2). Hence, we adopt wastewater emissions and sulfur dioxide emissions, which are reported in the most detail, as our dependent variables in this paper.

Control variables. We collect a set of prefecture-level variables to be used as controls in our empirical model to mitigate the problem of omitted variables. The control variables are constructed as follows: (1) *LnPgdp* is the natural logarithm of the prefecture-level GDP per capita; (2) *LnPop* is the natural logarithm of the prefecture-level total population; (3) *Density* is the population density, measured by the proportion of population to total land area; (4) *Indstr* is defined as the industry structure, measured by the proportion of added value of the second industry to the GDP; (5) *Fiscal* is the natural logarithm of the prefecture-level government fiscal expenditure. The summary statistics of the main variables used in this paper are presented in Table 1.

Table 1. Summary statistics.

Variable	Obs	Mean	Std. Dev	Min	Max
LnWater	2990	8.061	1.389	0.693	11.477
$LnSO_2$	2990	9.995	1.335	0.693	13.258
$Treat \times Post$	2990	0.026	0.159	0	1
LnPgdp	2990	10.641	0.593	8.576	13.056
LnPop	2990	5.820	0.785	2.160	8.137
Density	2990	5.726	0.925	1.609	7.882
Indstr	2990	0.469	0.109	0.106	0.897
Fiscal	2990	0.214	0.154	0.044	2.349

3.2. Empirical Results

3.2.1. Baseline Results

In this section, we provide our baseline results on the causal effects of regional environmental collaborative legislation and pollution emissions. We add control variables in a stepwise manner to estimate Equation (1) as our baseline regression. We further consider the robust standard errors of clustered prefectures to address the serial correlation and the effects of the heteroskedasticity problem on the estimation results.

Table 2 reports the baseline results. Columns 1 and 3 report a simple DID specification that only includes the DID estimator and fixed effects. Our DID estimator, *Treat* × *Post*, is statistically significant and negative, suggesting that prefecture-level wastewater emissions and sulfur dioxide emissions significantly decreased after the establishment of regional environmental collaborative legislation. In columns 2 and 4, some time-varying prefecture-specific characteristics, such as GDP per capita, total population, population density, industrial structure, and fiscal expenditure, are contained in the regression. We find that the DID estimator is still significantly negative, while the estimated coefficients of the controls are consistent with our expectations. As for the control variables, the coefficient of the GDP per capita is significantly negative at the 1% significance level, indicating that prefectures with higher levels of economic development are able to suppress their wastewater emissions, to a greater extent. In addition, the estimated coefficients of population size and industrial structure are significantly positive, which means that prefectures with a high population size and a high industrialization proportion will significantly increase their prefecture-level wastewater emissions. The significant impact of industrialization on pollution emissions also holds true in the examination of sulfur dioxide emissions. However, the estimation results indicate that population density and fiscal expenditure do not have a significant impact on prefecture-level pollution emissions. Overall, the baseline results in Table 2 demonstrate that regional environmental collaborative legislation significantly enhances the environmental governance capabilities, thereby inhibiting pollution emissions at the prefecture level.

Table 2. Baseline results.

	Dependent Variable: Pollution Emissions			
	(1)	**(2)**	**(3)**	**(4)**
	Wastewater Emissions		**Sulfur Dioxide Emissions**	
Treat × Post	−0.183 ***	−0.197 ***	−0.284 ***	−0.266 ***
	(0.058)	(0.058)	(0.065)	(0.067)
LnPgdp		−0.191 ***		−0.091
		(0.071)		(0.072)
LnPop		0.887 ***		−0.257
		(0.164)		(0.165)
Density		−0.280		−0.322
		(0.282)		(0.298)
Indstr		0.935 ***		1.163 ***
		(0.347)		(0.304)
Fiscal		−0.178		0.250
		(0.130)		(0.196)
Prefecture FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
N	2990	2990	2990	2990
Adj. R	0.921	0.923	0.880	0.881

Note: *** indicates significance at 1%. Standard errors in parentheses are robust and clustered.

3.2.2. Validity Test

Parallel trend test. The key identifying assumption in our empirical strategy is that trends related to pollution emissions are the same among treated and untreated prefectures in the absence of regional environmental collaborative legislation. We therefore conduct

a parallel trend test to check the identifying assumption of the difference-in-difference estimation. If the parallel-trend assumption holds, we should see no significant difference between the trend of treated and untreated prefectures in regards to pollution emissions before the policy shock. Specifically, we extend the DID specification to an event study by including a series of dummy variables in the standard regression to trace out the year-by-year effects of regional environmental collaborative legislation on pollution emissions. Using the following specification, we consider a ten-year window spanning from five years prior to legislation until five years afterwards.

$$Pollution_{ict} = \alpha + \beta_1 Treat_c \times Post_t^{-4} + \ldots + \beta_{11} Treat_c \times Post_t^{+5} + X'_{it}\gamma + \lambda_i + \lambda_t + \varepsilon_{ict} \quad (2)$$

where *Post* is a series of the pre- and post- policy year dummy variables. The vectors X are time-varying prefecture-level control variables. We should not expect any significant effects in the interactions; otherwise, that could indicate the existence of some underlying confounding factors. As shown in Figure 2, the solid line represents the estimated coefficient, and the dashed line represents the 95% confidence interval. None of the coefficients under the pre-treatment period reveal any statistical implications, and they show a similarly small economic magnitude. This indicates that the treated and untreated prefectures followed similar time trends at least five years before the policy shock. Then, note that pollution emissions decline rapidly two years after legislation, such that $Post^{+3}$ is negative and significant at the 5% level, indicating that legislation effects have a two-year lag. In addition, with the adoption of the regional environmental collaborative legislation, the differences in pollution emissions between the treatment group and control group start to diverge. Overall, this common-trend test helps to resolve a concern regarding the anticipation effect and further confirms the validity of our identification strategy.

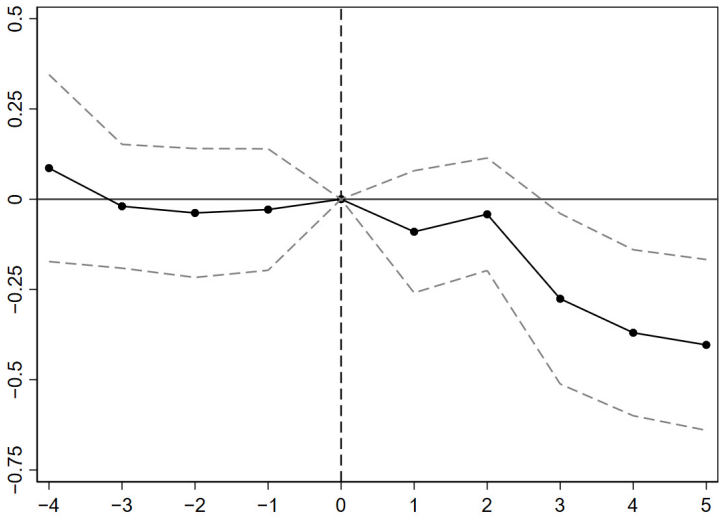


Figure 2. The parallel trend test of regional environmental collaborative legislation.

Placebo test. To address the concern concerning the non-random selection of the treatment group and the post time, we conduct a placebo test by randomly generating the treatment group and post time. Specifically, we first randomly select 10 provinces from the 31 provinces in the sample and assign them as a new treatment group; then, we randomly select a year from 2011 to 2018 (to make sure we have at least one year before the treatment and one year after the treatment for our DID analysis) as the year for legislation; finally, we construct a false regressor of interest, $Treat_{cfalse} \times Post_{tfalse}$, from these two randomizations. Given the random generating process of the data, we expect that the results should show no significant effect; otherwise, it may indicate the misspecification of our difference-in-differences model. We therefore conduct this random test 500 times to enhance the veracity of the placebo test. The result is reported in Figure 3, the line represents the kernel density

curve of the estimated coefficients, and the circles represent the p-value corresponding to each estimated coefficient. It is easy to observe that the distribution of estimates is centered around zero, showing an approximately normal distribution. The vast majority of estimates are not statistically significant (i.e., *p*-values > 0.05). Evidently, the result is highly insignificant, leading additional support to the validity of our research design.

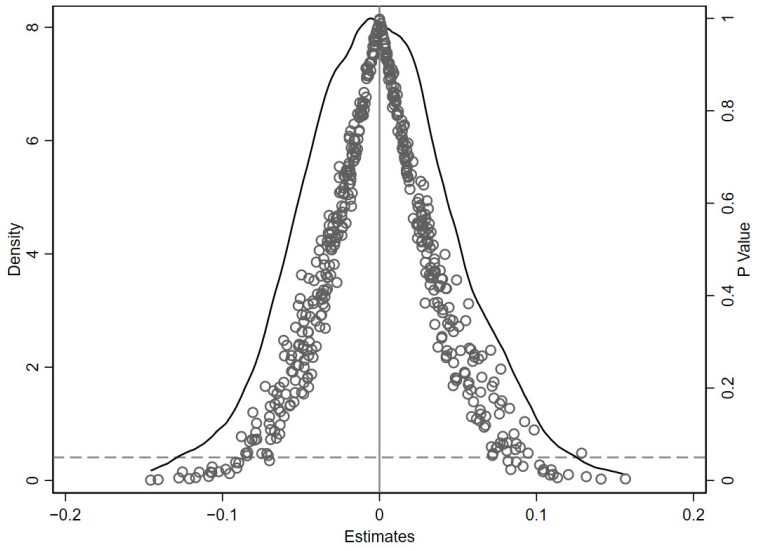


Figure 3. Distribution and *p*-values of estimates in placebo test.

4. Practical Challenges and Policy Suggestions Regarding Regional Environmental Collaborative Legislation

In the third section, we employed a difference-in-differences model to examine the impact of regional environmental collaborative legislation on the effectiveness of prefecture-level environmental pollution. We found that regional environmental collaborative legislation has a significant effect on reducing urban environmental pollution within collaborative regions. However, in practical terms, hindered by local profit-seeking behavior, a singular legislative hierarchy, and a lack of regional cooperation mechanisms, the full potential of regional environmental collaborative legislation cannot be realized. Therefore, in the face of these real obstacles, to fully harness the inhibitory effect of regional environmental collaborative legislation on urban environmental pollution, efforts should be directed towards establishing cross-regional environmental protection cooperation mechanisms and negotiation platforms for infrastructure development, strengthening horizontal collaboration mechanisms between regions, and improving vertical power distribution mechanisms among regions.

4.1. Practical Challenges: Practical Challenges in Regional Environmental Collaborative Legislation

4.1.1. Serious Local Profit-Driven Behavior in Regional Environmental Legislation

When examining the administrative regional divisions in China, it becomes evident that the profit-seeking behavior of local governments can impact the effectiveness of regional environmental legislation. The multifaceted roles of regional environmental legislation lead to local profit-seeking behavior and consequently, suboptimal legislative outcomes. The exercise of legislative authority in regional environmental collaborative legislation is achieved through negotiations among various regional administrative entities to address matters related to ecological environmental benefits, safety, natural resource development and management, ecological protection planning, and other related issues within the environmental region. This necessitates negotiation and the resolution of interrelated issues among different regions. However, when there are numerous stakeholders involved, it inevitably increases the complexity of negotiations. Balancing interests is a

critical perspective when studying the establishment and implementation of agreements in regional environmental collaborative legislation. Local administrative entities tend to prioritize their self-interest, and in practice, their participation in collaborative legislation is often driven by the pursuit of maximizing their own interests, resulting in a situation where "localism" and "formalism" prevails. Localism not only generates issues of negative externalities, but neither is pure local autonomy conducive to solving regional problems [23]. This is particularly challenging for regions with relatively less developed and unbalanced regional economic growth, such as thein the case of Beijing and Hebei Province. If regional environmental legislation does not have the common pursuit of overall benefits as its goal, and if legislative entities do not participate in collaborative legislation as members of a shared interest community, it becomes difficult to harness the initiative and enthusiasm of local legislative entities. In such cases, the distinctive "collaborative" characteristic of collaborative legislation becomes superficial.

Strong local governments tend to utilize their authority to formulate environmental regulations that align with their specific regional characteristics, often prioritizing local characteristics over collaborative aspects. Regional collaborative development is an important strategic initiative in China, aimed at addressing common needs and challenges encountered during regional reform and development. However, administrative entities within their respective administrative boundaries often maintain relatively high administrative barriers between entities from other administrative regions. "Governance by law is the most stable and reliable mode of governance, and a complete legal system solidifies the foundation of the national governance system" [30]. Regional environmental collaborative legislation represents an innovative approach to local legislation and to some extent, helps break down administrative barriers, infusing fresh perspectives into environmental governance. However, the current practice of collaborative legislation in various regions of China typically involves separate deliberations for individual regions. Many legislative projects tend to favor local interests rather than to fulfill the needs of regional collaborative development. In other words, it exhibits legislative characteristics of "negotiation but separate legislation," causing legislation to ultimately lean towards local characteristics rather than towards consolidating regional consensus. Regional environmental collaborative legislation should aim to align the practical requirements with the actual governance effects brought about by collaborative legislation, rather than to use the quantity of collaborative regional legislation as the sole criterion of the quality of it. Local entities should exercise legislative authority based on the actual needs of regional collaborative development and collaboratively enact regulations and rules with regional characteristics. However, based on the existing locally enacted regulations, this regional characteristic is not particularly prominent.

4.1.2. Singular Legislative Hierarchy in Regional Environmental Collaborative Legislation

From the perspective of the vertical legislative hierarchy in regions, the legislative level of regional environmental collaborative legislation tends to be relatively singular, and it does not fully mobilize the governance roles of multi-level legislative entities between regions. The distinctions among the majority of regional environmental collaborative legislative models mentioned in previous sections are mainly based on the consistency of local regulations among collaborative parties. However, there has been no differentiation in terms of legislative entities, effectiveness hierarchy, or legislative objectives [31].

Taking the effectiveness hierarchy as an example, the majority of scholars, legislative researchers, and legislative practices have limited their research scope on regional environmental collaborative legislation to local regulations enacted by provincial-level people's congresses and their standing committees. This approach overlooks the fact that prefecture-level cities and autonomous prefectures can also establish mechanisms for regional collaborative legislation. As a result, within a province, there is often no vertical collaboration, and between two provinces, there is no collaborative legislative model at a lower level. For instance, in June 2023, the cities of Hegang and Jiamusi in Heilongjiang

Province jointly implemented collaborative legislation for the protection of the Dulu River Wetland Nature Reserve, planning to enact the "Dulu River Wetland Protection Regulations". However, upon investigation, it was found that this regulation is not in harmony with or connected to the provincial-level collaborative legislation for wetland protection among the Three Northeast Provinces.

Regarding collaborative legislative models for river basins, the majority of provinces tend to enact legislation independently within their respective jurisdictions. Only a few provinces have begun to explore collaborative legislative models for river basins [32]. Particularly for rivers that span two provinces and two prefecture-level cities, in the absence of a provincial-level collaborative legislative framework, there is often a situation where only two different provinces' prefecture-level cities engage in collaborative legislation. The question arises of whether it is necessary to first establish a provincial-level collaborative legislative framework or whether the two prefecture-level cities can engage in collaborative legislation directly or through delegation. If it is deemed necessary to establish a provincial-level collaborative legislative framework first, it may constrain collaborative legislation, to some extent, at the prefecture-level city level. Conversely, it may lead to a disjointed situation where prefecture-level city-level collaborative legislation is not aligned with provincial-level collaborative legislation.

4.1.3. Inadequacy Regarding Regional Environmental Legislation Cooperation Mechanisms

From an overall perspective, there are insufficient regional collaborative mechanisms regarding environmental legislation, and local environmental legislation predominates over regional collaborative legislation. First, it is necessary to distinguish between regional environmental legislation and local environmental legislation. Some scholars argue that, while both narrow-sense regional environmental legislation and local environmental legislation primarily focus on ecological environmental protection, narrow-sense regional environmental legislation is based on the integrated development of multiple administrative regions, whereas local environmental legislation is based on a single administrative region. In other words, narrow-sense regional environmental legislation is a collaborative effort among multiple administrative regions to formulate legislation, while local environmental legislation applies only within a single administrative region [13]. Furthermore, narrow-sense regional environmental legislation needs to encompass the vast majority of ecological environmental protection requirements within that region, which is comprehensive, overarching, and possesses certain economic attributes.

In the comparative research conducted by the authors regarding the Three Northeast Provinces, the Yangtze River Delta, and the Beijing—Tianjin—Hebei regions, there is an ample supply of local environmental legislation, but there is a deficiency in narrow-sense regional environmental legislation. In the Yangtze River Delta's regional environmental collaborative legislation, the "Decision on Promoting and Ensuring the Construction of the Demonstration Zone for Integrated Development of Ecological and Green Integration in the Yangtze River Delta" aligns with narrow-sense regional environmental legislation. However, the Three Northeast Provinces lack such related legislation. The existing widespread local regulations mostly fall under watershed legislation or local environmental legislation. Although they all fall under the broad-sense regional environmental legislation, there is a lack of narrow-sense regional environmental legislation to comprehensively coordinate regional environmental collaborative legislation. Empirical research indicates that in the absence of cooperation, fragmented governance models lead to the degradation of water bodies in transboundary river basins [33]. The relationship between narrow-sense regional environmental legislation and specific object-based local environmental legislation, such as watershed environmental legislation, pertains to the relationship between the general and specific provisions of environmental legal norms within this region. The absence of narrow-sense regional environmental legislation is akin to losing the general provisions, and the environmental legislation for specific objects can only rely on laws or administra-

tive regulations as the superior legal basis, thereby losing the targeted and collaborative advantages of regional environmental legislation.

4.2. Policy Suggestions: Adaptive Measures for Regional Environmental Collaborative Legislation

4.2.1. Infrastructure Development: Establishing Cross-Regional Environmental Protection Cooperation Mechanisms and Negotiation Platforms

Establishing cross-regional environmental protection cooperation mechanisms and negotiation platforms is essential to provide institutional support for regional environmental legislative cooperation. A lack of cooperation mechanisms and communication channels is a significant challenge in the process of regional environmental legislative cooperation. Difficulties in reaching agreements and resolving differences often stem from conflicts of local interests [34]. New regionalism advocates for the voluntary cooperation of regional authorities, effectively addressing cross-regional challenges that localism fails to resolve. It also promotes regional equity among localities and fosters collaboration at the local level [35]. Therefore, cooperation and communication among governments and various stakeholders are crucial in cross-regional environmental protection. However, existing cooperation mechanisms are relatively weak, and communication channels are often not well-established, resulting in insufficient information sharing and increased conflicts of interest. In such a situation, regional environmental legislative cooperation faces challenges concerning making progress.

The implementation of environmental law should not be rigid. Negotiable implementation can enhance the flexibility of enforcing environmental laws [36]. The establishment of cross-regional environmental protection cooperation agencies and mechanisms, along with negotiation platforms, should consider the needs of all relevant parties. These platforms should facilitate information sharing and coordination, allowing regional governments to deeply collaborate and advance regional environmental legislative cooperation together. There are various forms of collaboration for stakeholder participation in environmental legislation, such as forming partnerships, holding ad hoc roundtable discussions, establishing regular advisory committees, and developing directive management plans or frameworks [37]. Balancing choices among multiple stakeholders is also a practical challenge in regional environmental legislative cooperation. Regional environmental legislative cooperation involves numerous stakeholders, including governments, enterprises, and residents, whose interests may conflict and differ. At this point, it is essential to balance economic, social, and environmental interests; to ensure public participation and adherence to the rule of law; to follow the principles of sustainable development; and to harmonize the interests of all parties involved.

4.2.2. External Drivers: Strengthening Horizontal Collaboration Mechanisms in Regional Environmental Legislation

Breaking away from a singular legislative hierarchy involves establishing and strengthening horizontal collaboration mechanisms between regions. The entities responsible for regional environmental collaborative legislation have been explicitly defined, with various legislative bodies playing a primary role in the collaboration mechanisms for regional environmental legislation. Although local governments are not the main legislative entities, they and their departments are significant participants in regional collaborative legislation. Addressing issues of regional environmental collaborative legislation also requires the joint efforts of governments at all levels, as well as relevant stakeholders.

On one hand, all legislative bodies should prioritize the overall interests of the region, breaking away from the notion of acting independently at the local level, and adopting a collaborative concept as a common principle. Relevant legislative working groups or special committees could be established, responsible for coordinating the legislative work of various departments and regions, while at the same time, strengthening the top-level design of regional environmental collaborative legislation, enhancing the guidance of the National People's Congress and its special committees on regional collaborative legislation. Clear legislative principles should be established, including unified standards, cooperative

governance, and the division of labor, to regulate the actions of legislative entities to avoid inconsistencies in the implementation of regulations and rules; legislation should adhere to the principle of differential management, taking into account the differences in environmental protection among regions, such as geographical location, resource conditions, development levels, etc., and adjusting measures and policies flexibly to adapt to the actual conditions of different regions. This approach would enhance the specificity and operability of legislation, allowing regions to adopt measures tailored to their specific conditions for better environmental protection outcomes.

On the other hand, "the competitive behavior among local governments in China is primarily determined by the system of fiscal decentralization and political centralization [38]"; thus, clarifying the functional positioning of local governments in regional environmental collaborative legislation can improve the specificity and operability of legislative work, promoting overall collaboration and governance of regional environments. Local governments have an important functional position in regional environmental collaborative legislation. Firstly, local governments should fulfill precise execution responsibilities, formulating specific environmental protection regulations within the legal framework set by the central government. Given the differences in environmental characteristics, resource distribution, and development needs between regions, local governments require flexibility and adaptability to legislate according to the actual conditions of their region. Secondly, local governments undertake important tasks in regards to resource allocation and supervision in regional environmental collaborative legislation. Local governments should allocate environmental protection resources according to the resource conditions of their region, ensuring that environmental protection efforts are effectively supported and guaranteed. Thirdly, local governments also need to supervise and evaluate the implementation of environmental protection efforts, identifying problems in a timely manner and taking appropriate measures to address them.

4.2.3. Internal Collaboration: Enhancing Vertical Decentralization Mechanisms in Regional Environmental Legislation

The regional environmental collaborative legislation collaboration mechanism includes both vertical collaboration from superior to subordinate legislation and collaboration among various levels of collaborative legislative entities. Currently, the regulations for China's collaborative legislative collaboration mechanisms are relatively rudimentary, with unclear division of legislative authority among entities. Particularly, there is a lack of substantive collaborative legislation vertically across regions, and enthusiasm for such collaboration is not high. Therefore, it is necessary to establish an integrated environmental protection legal framework to improve the legal system and legislative procedures.

From the perspective of the level at which legislative power is exercised, the relationship between the provincial and municipal district levels regarding collaborative legislative powers should be clarified [39]. Legislative powers can be granted to municipal and district governments through authorization norms. For instance, it should be specified that "in the absence of provincial-level local environmental collaborative legislation, municipal-level local environmental collaborative legislation relevant to the city can be formulated; where provincial-level local environmental collaborative legislation exists, it should be further detailed according to the provisions of the provincial collaborative legislation and reported to the relevant ecological and environmental authorities for the record".

While decentralizing powers, it is essential to ensure the systematic nature of legislation and to strengthen the research and formulation of laws for regional environmental collaborative legislation to ensure that the laws are targeted and operable. "Legislative principles are significant norms for legislative bodies to engage in legislative activities and represent the inherent spirit and character of legislation" [40]. It is necessary to establish fundamental principles and standards for cross-regional environmental protection to reduce the differences in environmental laws and regulations across vertical levels, to ensure consistency and coherence among relevant laws and regulations at different levels, and to

avoid legislative conflicts and duplications. Particularly, issues of non-cooperation across vertical hierarchies, which may manifest as objections to environmental permits, loopholes in environmental regulation, and citizen non-compliance with environmental policies [41], may exist. Therefore, it is necessary to perfect the legislative process, including extensively soliciting opinions from all parties, scientifically assessing the effects of legislation, etc., to enhance the scientific nature and transparency of legislation, and to unify, coordinate, and connect relevant environmental laws and regulations.

In terms of the specific content of the exercise of legislative power, focusing on the narrow-sense of regional environmental collaborative legislation based on the current issues of loose legislative structure and insufficient supply of regional environmental collaborative legislation, providing a general foundation for the broad-sense of regional environmental collaborative legislation is prioritized.

5. Discussion

Building upon existing research, this study conducted both quantitative and qualitative analyses. The quantitative analysis collected regional environmental collaborative legislation documents from the three major regions of China: the Three Northeast Provinces, the Yangtze River Delta, and the Beijing—Tianjin—Hebei region. Using balanced panel data from 299 prefecture-level cities in China from 2010 to 2019, a DID model was constructed to empirically test the impact of regional environmental collaborative legislation on the emission of environmental pollutants in prefecture-level cities. In addition, a qualitative analysis was conducted to examine the challenges faced by China's regional environmental collaborative legislation model in practice. Based on these analyses, policy recommendations for optimization were proposed.

5.1. Discussion on Quantitative Analysis

This study manually collected regional environmental collaborative legislation documents from the three major regions of China: the Three Northeast Provinces, the Yangtze River Delta, and the Beijing—Tianjin—Hebei region. Based on this, balanced panel data from 299 prefecture-level cities in China from 2010 to 2019 were utilized to construct a DID model to empirically test the impact of regional environmental collaborative legislation on the emission of environmental pollutants in prefecture-level cities. By examining how local governments promote the formation and implementation of inter-regional environmental collaborative legislation, and through discussing the economic impact of this environmental policy on urban pollution emissions, this study aims to advance existing research. According to the empirical research results, the implementation of regional environmental collaborative legislation effectively inhibits the discharge of wastewater and sulfur dioxide emissions in prefecture-level cities, indicating significant environmental governance effects of this policy, which is consistent with the evidence obtained in the existing literature. Zhang and Shang (2018), using a coupling assessment model, found that China's regional environmental collaborative governance has a strong effect on pollutant reduction [22]. Xin et al. (2024) employed a synthetic control method to discuss the impact of regional coordinated environmental policies on pollutant emission reduction in the Beijing—Tianjin—Hebei region and found that these policies effectively reduce atmospheric pollutant emissions in the region [42]. Unlike the aforementioned literature, this study employs a DID model to empirically test the environmental governance effects of regional environmental collaborative legislation in the three major regions of China. This not only examines the economic impact of regional environmental collaborative legislation on urban pollution emissions on a larger geographical scale, but it also provides richer quantitative evidence for examining the policy effects of regional environmental collaborative legislation obtained in existing research methods.

5.2. Discussion on Qualitative Analysis

This paper systematically introduces the current regional environmental collaborative legislation model adopted by the Chinese government in response to regional environmental challenges. It examines the challenges faced by this model in practice, including issues related to localism, legislative authority allocation, and conflicts and coordination between collaborative legislation and existing local environmental legislation. As a result, policy recommendations are proposed, emphasizing the establishment of cooperative mechanisms, coordination among stakeholders, and distribution of local legislative authority. Compared to the existing literature, this study makes several new contributions. Firstly, it addresses the lack of analysis on governance challenges faced by unitary states like China in addressing regional environmental issues. The existing literature predominantly focuses on discussions regarding the coordination issues between federal and state governments in federal systems like those in the United States, neglecting research on policies for regional environmental collaboration in highly centralized unitary states. For instance, Stewart (1977) discussed the challenges faced by federal states in implementing environmental policies [6]. Fisch (2018) compared the advantages and disadvantages of federal and unitary states in executing environmental policies but does not introduce the latest regional environmental collaborative legislation model adopted by China [1]. Secondly, this study provides valuable policy recommendations for optimizing cooperation among local governments of the same rank through legislative models for environmental governance. The existing research mainly discusses the power struggle between higher and lower ranking governments regarding environmental regulation, while overlooking discussions on environmental cooperation among governments of the same rank. For example, Adler (2020) proposed resolving conflicts between federal and local governments regarding environmental jurisdiction but did not provide research concerning the cooperation and challenges in environmental governance policies among local governments of the same rank [3].

5.3. Limitations and Directions for Future Research

This paper holds certain limitations in both quantitative analysis and qualitative aspects.

In terms of quantitative analysis, we utilized city-level data from China spanning the years between 2010 to 2019 and employed a DID model to empirically test the environmental governance effects of regional environmental collaborative legislation. Therefore, this paper exclusively discusses the policy impacts of regional environmental collaborative legislation within the context of China. Due to significant differences among countries in regards to legislative models and environmental governance, the research conclusions obtained in this paper can only support the specific scenario of China. Future research should explore the topic from a broader international perspective, considering the backgrounds of multiple countries. Additionally, while this paper employed a DID model as the empirical research method, the conclusions derived from using a single quantitative research method still possess uncertainties, to some extent. Hence, future research can employ more scientifically rigorous quantitative analysis methods to analyze the subject, ensuring that the positive policy impacts of regional environmental collaborative legislation on environmental pollution control become a consensus in the existing research.

In terms of qualitative analysis, we analyzed the challenges facing China's regional environmental collaborative legislation and proposed policy recommendations. However, this study only focused on the difficulties encountered by China's regional environmental collaborative legislation, without delving into the challenges faced by environmental federalism governance models predominant in other countries. This limitation suggests that the research material in this paper may not be comprehensive enough. Future studies could compare regional environmental collaborative governance models in other countries to provide more international comparative examples for addressing regional environmental issues. Additionally, the policy recommendations in this paper mainly discuss collaboration issues among local governments of the same rank, lacking an observation from a macro perspective at the central government level. Therefore, future research could include an

analysis of the functions of and roles played by the central government in facilitating collaboration among local governments of the same rank, thereby offering a more comprehensive research perspective for optimizing the regional environmental collaborative legislation.

6. Conclusions

This paper focuses on the regional environmental collaborative legislative system of China, as the largest unitary state, aiming to evaluate the effectiveness of this system through qualitative research and to examine the practical challenges through qualitative analysis, thereby providing beneficial institutional recommendations. Initially, the paper examines the collaborative legislative models of the three most representative regions in China, summarizing that the regional environmental collaborative legislative system is characterized by voluntary cooperation among local governments, with collaborative legal texts serving as action guidelines. Subsequently, to assess the effectiveness of the impact of regional environmental collaborative legislation on environmental governance, the paper conducts empirical testing using balanced panel data from 299 prefecture-level cities in China from 2010 to 2019, constructing a DID model, and finding a significant inhibitory effect of regional environmental collaborative legislation on pollution emissions at the city level. Specifically, the implementation of regional environmental collaborative legislation results in a 19.7% reduction in prefecture-level wastewater emissions and a 26.6% reduction in sulfur dioxide emissions. Finally, to optimize this beneficial mechanism and enhance environmental governance, the paper investigates the challenges faced by regional environmental collaborative legislation, such as localism, difficulties in local legislative authority allocation, and inadequate cooperation mechanisms among local governments of the same rank. It also proposes policy recommendations, such as building a cooperation platform, coordinating the interests of stakeholders, and improving the distribution mechanism of environmental legislative power.

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References

1. Fisch, J. The Case for Effective Environmental Politics: Federalist or Unitatry State? Comparing the Cases of Canada, the United States of America, and the People's Republic of China. *Univ. Mich. J. Law Reform* **2018**, *51*, 777–807. [CrossRef]
2. Millimet, D.L. Environmental Federalism: A Survey of the Empirical Literature. *Case West. Reserve Law Rev.* **2014**, *64*, 1669–1757. [CrossRef]
3. Adler, J.H. Uncooperative Environmental Federalism 2.0. *Hastings Law J.* **2020**, *71*, 1101–1126.
4. Marks, G. Structural Policy and Multilevel Governance in the EC. In *The State of the European Community*; Cafruny, A., Rosenthal, G., Eds.; Lynne Rienner: Boulder, CO, USA, 1993; Volume 2, pp. 391–409.
5. Jänicke, M.; Quitzow, R. Multi-level Reinforcement in European Climate and Energy Governance: Mobilizing economic interests at the sub-national levels. *Environ. Policy Gov.* **2017**, *27*, 122–136. [CrossRef]
6. Stewart, R.B. Pyramids of Sacrifice? Problems of Federalism in Mandating State Implementation of National Environmental Policy. *Yale Law J.* **1977**, *86*, 1196–1272. [CrossRef]
7. Collins, R.; Johnson, D.A. Collaborative water management across England—An overview of the Catchment Based Approach. *Environ. Sci. Policy* **2020**, *112*, 117–125. [CrossRef]

8. Kimura, S. Inter-Municipal Cooperation and Regional Waste Management in Japan. In *Regional Waste Management–Inter-Municipal Cooperation and Public and Private Partnership*; Kojima, M., Ed.; ERIA: Jakarta, Indonesia, 2020; Volume 12, pp. 10–60.
9. Feng, R. Construction of a Coordinated Evaluation System for Regional Environmental Protection Legislation in the Beijing-Tianjin-Hebei Region. *Soc. Sci.* **2018**, *7*, 111–116.
10. Liu, F.; Xu, H.H. Influencing factor configuration and path research on the Chinese government's regional environmental governance. *China Population Resour. Environ.* **2023**, *9*, 98–110.
11. Briffault, R. Localism and Regionalism. *Buffalo Law Rev.* **2000**, *48*, 1–30. [CrossRef]
12. Meng, Q.Y. On the Cooperative Legislation Safeguard Mechanism of the Jing-Jin-Ji Region's Environmental Governance. *J. Politics Sci. Law* **2016**, *1*, 121–128.
13. Wang, X.P. Research on Coordination Model of Regional Environmental Legislation. *Environ. Protect.* **2018**, *46*, 44–47.
14. Huang, X.S.; Li, X.D. The Functional Positioning and Implementation Approach of Regional Environmental Collaborative Legislation. *Qinghai Soc. Sci.* **2023**, *3*, 159–170.
15. Yang, Z.A.; Qiu, G.A. The Logic Mechanism, Constraining Factors and Realization Route of the Fiscal Cooperation of the Regional Environment Governance. *Coll. Essays Finance Econ.* **2016**, *6*, 29–37.
16. Wang, Z.B.; Wang, H.Y. The Analysis of the Regional Environmental Collaborative Governance of Beijing-Tianjin-Hebei from the Perspective of Polycentric Governance Theory. *Ecol. Econ.* **2016**, *3*, 157–163.
17. Si, L.B.; Zhang, J.C. The Driving Mechanisms, Governance Models, and Practical Contexts of Cross-Administrative Regional Ecological Environmental Collaborative Governance: A Comparative Analysis Based on Typical Cases in Key Areas of National Ecological Governance. *Qinghai Soc. Sci.* **2021**, *4*, 46–59.
18. Chen, R.Y. Research on the System and Mechanism of Regional Environmental Collaborative Governance. *Environ. Protect.* **2023**, *51*, 40–43.
19. Zhou, N.Y. How Can Vertical Intervention Promote Local Collaborative Governance?: Evidence from the Yangtze River Delta's Regional Environmental Collaborative Governance. *Public Admin. Rev.* **2020**, *13*, 90–107.
20. Suo, L.; Li, X. Regional Public Affairs Governance from "Single Border" to "Multiple Borders"—Based on Observations of Cooperation in Air Pollution Prevention and Control in the Yangtze River Delta. *China Adm. Manag.* **2021**, *2*, 92–100.
21. Han, Y. Research on Performance Evaluation of Provincial Ecological Governance in China. *Stat. Res.* **2017**, *34*, 69–78.
22. Zhang, Y.; Shang, H. Collaborative Assessment of Ecological Vulnerability and Government Performance in Western China: Empirical Study on 45 Cities in Western China. *China Soft Sci.* **2018**, *8*, 91–103.
23. Bush, B.J. A New Regionalist Perspective on Land Use and the Environment. *Howard Law J.* **2012**, *56*, 207–252.
24. He, H.R. The Practice Patterns and Jurisprudential Reflections on Regional Collaborative Legislation in China. *Appl. Law.* **2020**, *21*, 69–78.
25. Shi, F.L.; Zhang, Z.Y. Justification of Regional Collaborative Legislative Power as a New Type of Local Legislative Authority. *Hebei Law Sci.* **2023**, *12*, 41–62.
26. Cheng, Q.D. The Resolution of Dilemmas in the Hierarchical Relationships of Regional Collaborative Legislation. *Law Sci.* **2022**, *10*, 32–44.
27. Zhou, J.; Qi, P.; Zhou, Y.; Ren, Q.; Liu, Z. Research on Dynamic Monitoring of Coordinated Development of Economy, Environment and High Haze Pollution Industries Such as the Thermal Power Industry in the Beijing–Tianjin–Hebei Region. *Energies* **2023**, *16*, 2582. [CrossRef]
28. Yang, H.; Jia, H.L. Researching on Problems and Solutions in Jointly Legislation by Jing-jin-ji Area. *Hebei Law Sci.* **2017**, *35*, 107–119.
29. Wang, J.; He, Y. Analysis on the Legislative Mechanism of Regional Environmental Cooperation Governance in Beijing, Tianjin and Hebei. *Hebei Law Sci.* **2017**, *35*, 120–130.
30. Fu, Z.T.; Fu, C.W. Research on Several Issues of the Rule of Law in National Governance. *Lanzhou Acad. J.* **2022**, *5*, 69–78.
31. Wen, Z.B. Constitutional Regulation of Regional Collaborative Legislation. *Law Sci.* **2023**, *8*, 29–41.
32. Ou, H. On Current Situation and Perfection Path of Local Watershed Legislation in China. *J. Nanjing Tech. Univ. (Soc. Sci. Ed.)* **2023**, *22*, 63–75+114.
33. Wang, X.; Wang, Y.; Pang, Y.; Wang, K.; Yu, J. Pollution Load Coordination and Eco-Compensation for Trans-Boundary Water Pollution Control: The Case of the Tri-Border Region of the Yangtze Delta. *Sustainability* **2024**, *16*, 1151. [CrossRef]
34. Yang, Q.W.; Xiong, X.Y. On the Improvement of Regional Collaborative Legislation under the Modernization of Social Governance—A Case Study of Legislative Model of Regulations on the Protection of Youshui River. *North. Forum* **2022**, *2*, 103–114.
35. Alexander, L.T. The Promise and Perils of "New Regionalist" Approaches to Sustainable Communities. *Fordham Urb. Law J.* **2011**, *38*, 629.
36. Owen, D. The Negotiable Implementation of Environmental Law. *Stanf. Law Rev.* **2023**, *75*, 137. [CrossRef]
37. Karambelkar, S.; Gerlak, A.K. Collaborative Governance and Stakeholder Participation in the Colorado River Basin: An Examination of Patterns of Inclusion and Exclusion. *Nat. Resour. J.* **2020**, *60*, 1.
38. Wang, M.J.; Lin, J.H.; Yu, Z.X. The External Fairness of CEO's Emolument, the Nature of Stock Right and Company's Performance. *J. Manag. World* **2010**, *3*, 22–31+187–188.
39. Song, F.; Hao, S.C. In-depth Examination and Discussion on Regional Collaborative Legislation. *Theor. Explor.* **2022**, *3*, 115–121.

40. Zhou, W.S. On the Legalization and Institutionalization of Legislative Principles in China. *Law Forum* **2003**, *3*, 29–36.
41. Lin, A.C. Uncooperative Environmental Federalism: State Suits Against the Federal Government in an Age of Political Polarization. *George Wash. Law Rev.* **2020**, *88*, 890.
42. Xin, K.; Zhang, R.; Zhu, Z.; Zhou, Y. Do Regional Coordinated Environment Regulations Reduce Pollutants? A Policy Evaluation on Environmental Governance Based on "Outlines of the Coordinated Development Planning for the Beijing-Tianjin-Hebei Region". *J. Financ. Econ.* **2024**, *4*, 1–15.

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Assessing Multilateral Development Bank ESG Safeguard Integration with International Sustainability Ratings

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Abstract: In an era where sustainability is paramount, this study critically assesses how multilateral development banks (MDBs) integrate internationally recognized sustainability indicators into their ESG safeguard policies. MDBs have historically incorporated policies to manage environmental and social risks in project financing; yet, protections against negative impacts in developing countries often remain insufficient. On the other hand, several infrastructure sustainability rating systems have been established around the world in recent decades due to economic growth and the importance of controlling environmental impacts associated with the construction sector. The purpose of this study was to analyze whether and how the indicators that these internationally recognized systems use to rate whether a project is sustainable are integrated into these safeguards by using several methodologies, including an analysis of existing documentation, a high-level matrix, and qualitative methods based on co-occurrences using specialized "atlas ti" software. The results show that MDBs' coverage of financial, governance, and country risks lacks the sustainability focus found in these rating systems. Therefore, this study that concludes MDB safeguards must evolve, balancing comprehensive sustainability parameters and detailed management guidelines and addressing impacts beyond statutory frameworks to encourage stakeholder engagement for more sustainable infrastructure projects.

Keywords: ESG safeguards; multilateral development banks; sustainable infrastructure; rating tools

1. Introduction

Multilateral development banks (MDBs) and other development finance institutions can play an important role in helping governments create an effective enabling environment for sustainable infrastructure through technical assistance and project preparation as well as in mobilizing private action [1]. To achieve this goal, these organizations have relied on the implementation of safeguarding policies accompanied by a deliberate effort to harmonize them while considering regional and stakeholder differences [2].

The development of these safeguard systems began in the 1990s as a tool for safeguarding sustainability in infrastructure projects. Since then, these systems have been actively updated in an attempt to bring together as many potentially affected social, environmental, and economic areas as possible [3]. Some authors agree that there has been little academic analysis of how these safeguard systems cover all the mandatory credits or parameters of international certification systems, but there is a broad consensus that they have improved in their comprehensiveness over the years [4]. These systems are incorporated into the governance of multilateral development banks as part of the tools available for decision-making, defining a set of environmental and social requirements that potential borrowers must meet during project design and construction. However, although they incorporate these requirements, they lack a system of clear and standardized indicators that can group together each of the areas they seek to ensure. As far as the different international

certification systems are concerned, there is no standardized or commonly agreed-upon methodology that offers a reliable measurement of sustainability throughout the life cycle of infrastructure [5]. Multilateral entities that provide funding for borrowers to undertake projects require guidelines and practical tools that allow them to monitor the impact generated during all stages of a project—tools that are also necessary for the governments and authorities involved [6,7]. This research seeks to contribute knowledge to a hitherto unresearched approach that seeks to identify the extent of the relationship between multilateral development banks' safeguard systems and internationally recognized infrastructure sustainability certification systems. This is an opportunity to carve a new niche into the academic landscape by departing from the existing literature, which mainly focuses on the role of multilateral development bank (MDB) environmental, social, and governance (ESG) safeguard policies in advancing project sustainability and the use of ENVISION and CEEQUAL for tracking sustainable progress in ongoing projects. Our investigation explores uncharted territory. This paper's novel analysis of the integration of credits and monitoring indicators from these international certifications into MDB safeguard policies presents a significant learning opportunity for the academic community and policymakers. By dissecting the extent and manner of this integration, this study lays the groundwork for refining these policies toward more effective and actionable strategies in the construction phases of projects. Ultimately, it ensures that projects not only adhere to best practices but are also directed by a robust framework equipped with clear and measurable indicators, marking a step toward operational excellence and enhanced sustainability outcomes for projects financed by these banks.

The main objective of this study was to answer the following question: Does MDB safeguard policies comply with all the items and indicators monitored in the credits of the international sustainability certificates? It also aimed to compare the safeguard policy systems available for each selected MDB in order to assess which MDB has the highest level of sustainability area integration, indicated by recognized infrastructures of sustainability certification schemes. This research is not an attempt to validate whether the current safeguards are individually successful but rather to ascertain the degree to which these policies adopt the sustainability approach of these international certificates. The specific objectives of this research were to, first, benchmark the performance of these safeguards in measuring sustainability against the criteria of the proposed certification schemes; secondly, provide a comparative analysis of the elements and scopes identified as priorities by the certification schemes and the extent to which they are featured in safeguards; and, third, identify challenges to improving the sustainability shielding of infrastructure projects financed by these bodies in the future. To this end, this work provides a broad overview of the state of the art of sustainability measurement. Finally, two major research needs are proposed to improve the integration of all the necessary aspects to be included in safeguards and covered during the design and construction of infrastructure projects.

2. Literature Review

2.1. ESG Safeguard Systems

To ensure sustainable development, development finance institutions have developed a set of original environmental and social safeguard policy documents that "describe how the Bank will address the environmental and social impacts of its projects" [8]. (See Figure 1). These safeguards are defined by each entity's legal framework and mandate and are tailored to the nature of the projects they implement and the local sensitivities of each region. MDBs like the World Bank Group have been pioneers in implementing robust environmental and social safeguard systems [9]. Therefore, the different existing safeguard policies exhibit great differences in approach and scope [10].

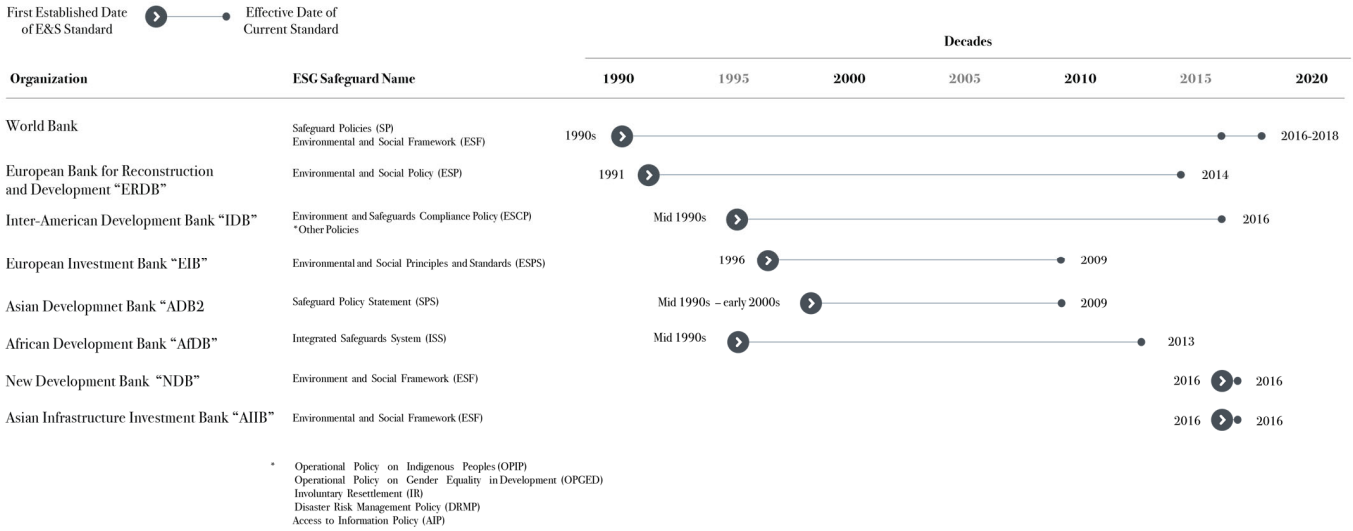


Figure 1. ESG safeguard timeline. Own elaboration based on various documents [8,10].

Research has shown that ESG factors can significantly impact bank performance and risk-taking behavior [11]. Banks that prioritize ESG considerations tend to exhibit better risk management practices and create long-term value for stakeholders. Additionally, studies have highlighted the importance of sustainability reporting in the banking sector, emphasizing transparency regarding ESG issues [12]. By disclosing ESG information, banks can enhance their reputation and demonstrate their commitment to sustainable practices.

Currently, there is a significant divergence in safeguard policy between development banks and the different regions in which they operate, with Western-backed development banks requiring borrowers to conform to developed country standards, while others, such as banks in China and Brazil, abide by host country standards [13].

Many organizations, due to this lack of real adaptation to the markets in which they operate, are revising and adapting their processes to the new paradigm of the global legal order, and a good example of this is the World Bank's new "Environmental and Social Framework" (ESF) that replaced the old "Safeguard Policies" that had gradually emerged since the 1980s in response to the harmful impacts of World Bank-financed investment projects [14]. The European Union has indeed made significant progress in advancing legislation related to environmental, social, and governance (ESG) issues. One notable directive is the "Non-Financial Reporting Directive" introduced in 2014, which mandates that large companies with over 500 employees disclose ESG information [15]. This directive has influenced the value relevance of ESG disclosure as firms voluntarily providing non-financial reports before its application have seen positive outcomes [16]. Additionally, the European Commission has deployed various financial instruments and funding to address energy poverty, showcasing a commitment to tackling social and environmental challenges [17]. Furthermore, the EU has endorsed integrated coastal zone management (ICZM) as a tool for managing complex coastal issues, highlighting a proactive approach to coastal governance and risk management [18]. These legislative efforts demonstrate the EU's dedication to promoting sustainability, transparency, and accountability in various sectors, contributing to a more sustainable and responsible business environment.

The analysis and design of the most sustainable scenarios for an infrastructure project are usually undertaken early in the project cycle, not least because it is at this stage that there is an opportunity to weigh up different options and consider alternative materials or even a different design, including the risks to which a project may be exposed throughout its life cycle. Consequently, multilateral development banks, which aim to support investment in sustainable infrastructure, could help through their safeguards to ensure the sustainability of infrastructure [1].

It is important to mention that the alignment of MDBs to this taxonomy seems to be a crucial and essential step [19], considering the incorporation of the EU taxonomy as a classification system for economic activities that can be considered environmentally sustainable, as published by the European Commission in March 2020. As authors such as those of [20] warn in their article "Environmental Impact Assessment for transport projects: A review of technical and process-related issues" regarding EIAs, this taxonomy system published by the EU is merely oriented toward the analysis of sustainability from an environmental point of view, so it seems reasonable to argue that both natural and socioeconomic aspects related to infrastructure projects should be integrated more efficiently. Although the proposed taxonomy is only environmentally focused, we believe that it will not take long to integrate a complete taxonomy, not only for environmental but also for social and economic monitoring purposes as well as for all types of infrastructure projects. When the relevant financial market actors, including multilateral development banks, start complying with the standards, the effectiveness of this classification system can be fully assessed [19].

The safeguards designed by MDBs generally do not follow international environmental and social standards but only monitor the minimum requirements among member countries [21]. The two authors of [21] also discuss accountability mechanisms with reference to the sustainability of projects funded by these entities and how they could be more effective. MDBs often play a key role in helping the recipient country improve socioenvironmental planning by establishing or reinforcing environmental and social requirements [22].

The environmental and social safeguard approach used by the major multilateral development banks (MDBs) requires a thorough rethink to address the gaps between project conceptualization and practice [3]. Despite the proven benefits of implementing these widely discussed safeguard policies, some studies emphasize that safeguards serve mainly to protect the banks themselves from criticism; that they do not affect most non-MDB-funded projects; that they are expensive, complicated, and highly bureaucratic; and that they provide no incentive for borrowing countries to improve their systems [23]. According to some authors [24], the integration of these safeguards into projects is not optimal, despite the constant and diverse adaptation of their policies, as these multilateral organizations are constantly undergoing reform, which indicates that there are only "good practices" instead of so-called "best practices". Therefore, there have been many attempts by these organizations to improve or verify their standards by benchmarking against external standards [1].

One of the main issues with measuring the impact of these safeguards is the paucity of open data disclosed by the organizations themselves on the outcome of using these tools. Qualitative scrutiny of disclosure standards, with an emphasis on aspects such as completeness of disclosure, accessibility of information, timeliness of information, and availability of resources, reveals that most development multilaterals operate under the strictest of corporate confidentiality principles, conflicting with the public demand for information [25].

Moreover, recent research in the field of sustainable finance, development outcomes, and ESG impact assessment methodologies has seen significant advancements. Studies such as [26] have focused on sustainable finance initiatives in Japan, highlighting public policy efforts to integrate ESG criteria into financial decision-making and promote sustainable finance [26].

The authors of [27] conducted a bibliometric and content analysis of ESG literature, revealing a growing interest in ESG within the sustainable finance domain, as evidenced by increasing publications and citations [27]. The authors of [28] developed a methodology for assessing transition finance, aligning with the finance for sustainable development approach and emphasizing the role of external finance sources in countries' transitions toward sustainability [28]. These studies collectively contribute to the evolving landscape of sustainable finance, development outcomes, and ESG impact assessment method-

ologies, providing valuable insights into the intersection of finance, sustainability, and governance practices.

As we have seen, many studies have examined the performance achieved by projects adopting ESG systems, not only in finance or infrastructure projects but also in other more exotic projects such as the work "Terrorist attacks and environmental social and governance performance: Evidence from cross-country panel data" [29], which goes beyond what is understood by the performance of sustainability, investigating the relationship between levels of terrorism and social and environmental performance measured in ESG terms.

2.2. Infrastructure Sustainability Certification Schemes

Sustainability assessment is a complex assessment method. It is undertaken to support decision-making and policy in a broad environmental, economic, and social context, and transcends a purely technical/scientific assessment" [30]. Sustainability rating tools (See Table 1) are a response to the need to translate high-level concepts and objectives into practical frameworks for infrastructure owners and design and construction professionals [22].

Table 1. Sustainability rating tools.

Tool	Certifying Body	Sector	Country
ASCE	American Society of Civil Engineers	All	US
CEEQUAL	Institution of Civil Engineers [31]	All	UK
ENVISION	Institute of Sustainable Infrastructure (ISI)	All	US
IS	Australian Green Infrastructure Council (AGIC)	All	Australia
GreenLITES	New York State Department of Transport	Transport	US
GREENROADS	University of Washington	Transport	US
I-LAST	Illinois Department of Transportation	Transport	US
INVEST	Federal Highway Administration (FHWA)	Transport	US
STARS	Portland Bureau of Transport	Transport	US

The construction sector has implemented different sustainability assessment and certification systems due to the need to understand construction from a sustainable development approach [32]. As a result of this effort, there are now a multitude of assessment and certification systems that measure and quantify the sustainability of infrastructure projects. They are often developed by governmental and non-governmental institutions and sometimes in collaboration with academia [33].

Some of the existing sustainability assessment systems are state-level and others are national [34]. These systems use different techniques to determine sustainability, emphasizing different sustainability factors, as proposed in "Toward more sustainable infrastructure" [35]. Based on the scientific community's accepted definition, the scope of sustainability assessments consists of the identification, prediction, and evaluation of the potential impact of different solutions or alternatives through the triple bottom line [36].

The different certification schemes currently recognized are designed to provide guidance, scoring, and potential rewards for using sustainable best practices [37]. Most of these schemes go beyond the existing minimum regulatory requirements imposed by the regulations of the countries where the projects are located.

Although these systems have undergone improvements following various reviews of their scope, they are often criticized because they tend not to fully consider economic and social aspects, to the detriment of environmental issues [38]. Some analysts suggest that infrastructure developers and owners considering the use of such sustainability rating tools should be aware of the focus and bias of the tools available on the market since, if only the requirements proposed by these rating tools are analyzed, the areas of sustainability more relevant to a project and its wider context may be overlooked [39].

Authors such as those of [33] analyze and describe some of the methods specifically designed to assess sustainability, such as rating systems, and conclude that they are incomplete as they do not consider aspects such as cost–benefit analysis, multi-criteria decision analysis, or environmental impact assessment methods. Many of the multilateral agencies and offices that incorporate infrastructure development under their mandates have not yet widely incorporated these rating systems in the evaluation of their projects [40], although they have been using this type of system since 2015 to evaluate their sustainability from a corporate point of view, such as the use of the GRI system, which is practically in general use by the organizations of the United Nations system. As a point to bear in mind, the rating systems are also deficient because they focus on developed economies and do not consider the integration of the local sensitivities and specific characteristics of the countries in which these infrastructures are developed [41].

There are three general infrastructure sustainability assessment and certification systems applicable to any type of infrastructure that assess projects following the principles of sustainability (ENVISION ISI, 2012; Civil Engineering Environment Quality "CEEQUAL", BRE Group, 2015; and Infrastructure Sustainability "IS" ISCA, 2012), although there are others that integrate infrastructures more oriented toward transport or building and that are not included in this study due to the specificity of their scope. There are elements in common between most of the systems analyzed for the assessment of the sustainability of infrastructure projects and that are presented under the pillars of Management, People, Resources, and the Natural World, although in some there are also more specific ones [42]. Although all these elements consider the most important aspects of sustainability, focusing on specific criteria, there are no major differences between them with respect to the requirements for an infrastructure project to be considered sustainable [41].

If we consider the nature of the assessment system itself from the point of view of the methodology used, it can be determined that most systems are usually associated with a common metric, usually called points or credits [5]. These rating tools are generally structured around a list of elements/criteria organized into main themes/categories, such as location, linkage, planning, sustainability, energy and water resources, materials, infrastructure, waste management, transport, land-use planning, social and economic well-being, and innovative design and technology [43], but, even so, there is no uniformity or standardization of criteria.

Some ranking systems such as CEEQUAL weigh each best practice equally, while others such as ENVISION set different levels of importance for each best practice. In conclusion, it should be mentioned that these systems, in terms of development history, strategy choices, evaluation structure, evaluation criteria, and local benchmarks, are very diverse [43].

Taking into account the analysis in "Sustainable Assessment of Transport Infrastructures Projects: A Review of Existing Tools and Methods" [5], four basic reasons for the desirability of these models are listed:

i. They provide a common metric for the whole range of sustainable solutions;
ii. They measure sustainability and, therefore, make it manageable;
iii. They allow direct communication of sustainability goals, efforts, and achievements;
iv. They provide a reasonable context in which designers, contractors, and material suppliers can be innovative in their solutions [44].

Some comparative studies reflecting the effectiveness and applicability of these systems can be found in the reference literature [45].

So, it has been highlighted that there are no previous publications that analyze what has been discussed in this paper. Of course, there are publications that analyze how MDBs, through their ESG safeguard policies, contribute to achieving the sustainability of projects and how ENVISION and CEEQUAL contribute to monitoring the progress of the sustainability of already implemented projects, as has been highlighted in this literature review, but there are none that analyze what is proposed in this paper, and that is why there is such a gap. By analyzing how and how many of these issues through the indicators

used by these international certificates are already integrated into safeguards policies, it will be much easier to move toward revising these policies and orienting them toward more operational and impactful approaches to projects during construction, ensuring that projects are not only subject to good practice but also to a structured framework with clear indicators.

3. Methodology

The aim of this study was to determine the degree to which the ESG safeguards used by MDBs in the design and implementation phase of infrastructure projects of all types are related to the credits that two internationally recognized and prestigious international systems use to determine the degree of sustainability of infrastructure projects. In the first stage, by way of bibliographic analysis, all the published documentation on sustainability certification systems was reviewed, as well as the MDBs' safeguard policies, in order to understand their scope. In the second or selective analysis stage, a series of variables were utilized to select the entities to be reviewed. In the third or qualitative analysis stage, two different tools were used. Firstly, a high-level matrix was created, which was a simplified version of the "ecosystem services matrix" [46], in which the relationship between safeguards and sustainability certification systems was analyzed and contrasted in a second phase of this stage by means of qualitative analysis using atlas ti software. In this last stage of qualitative analysis, it was necessary to define the indicators that allowed the coding and subcoding of the documents to be studied. These indicators, as well as the codes and subcodes generated, are available upon request.

The following Figure 2 shows the different stages and research methods undertaken in this study.

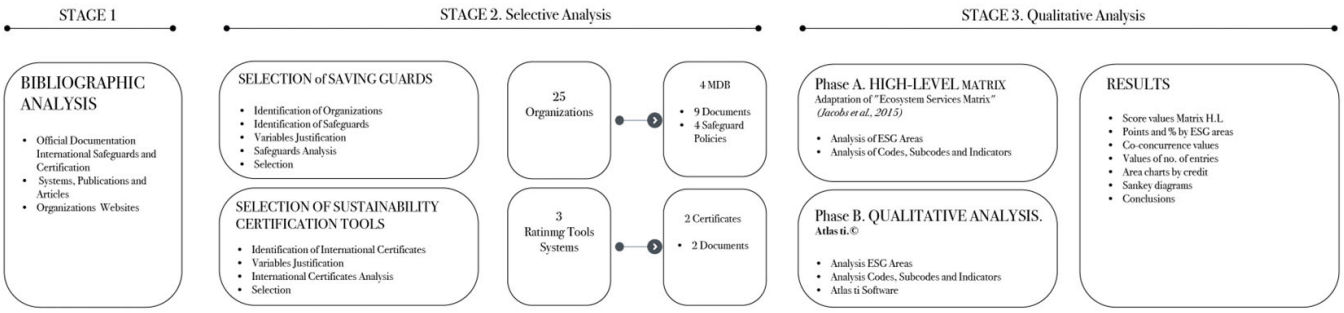


Figure 2. Stages of the methodology applied for this research. Own elaboration [46].

Figure 3 sets out the thematic areas and parameters that ESG safeguards seek to control in their projects and correlates directly with the codes in Table 4, categorized by the three dimensions of sustainability [29]. Each point in Table 4, such as, for example, "Pollution Prevention and Abatement" (MA.1) or "Indigenous Peoples" (S.1), is reflected in a specific code, providing a structured framework for systematic reference and management. In relation to this, Figure 4 details the essential components in the sustainability certification schemes, which are coded in Table 7, e.g., for the CEEQUAL scheme, "Flooding and Surface Water Run-Off" (2.2), or Welfare (QL1) for ENVISION. The purpose of these 2 figures and the tables was to compose a system of codes classified by area and parameter that allowed us to assess their interrelation both in the high-level matrix and in the qualitative analysis through co-occurrences.

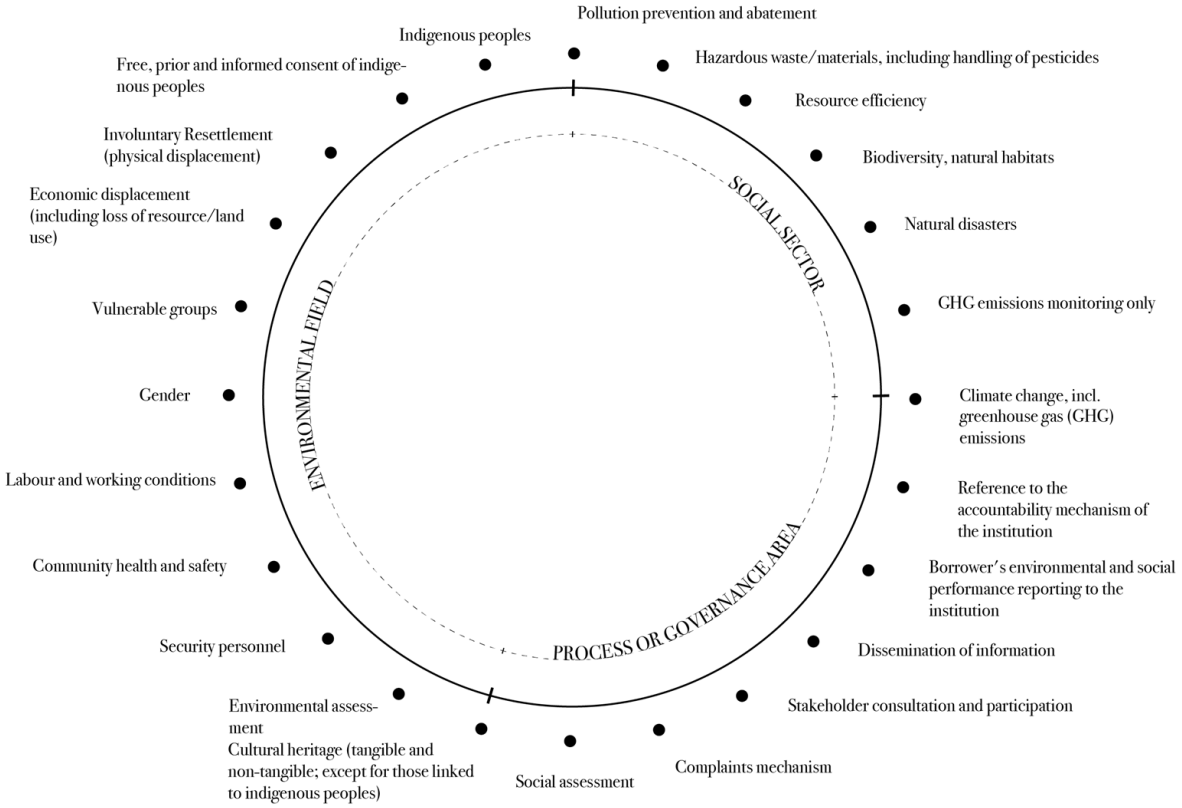


Figure 3. Areas and parameters controlled by ESG safeguards. Own elaboration based on several documents [10].

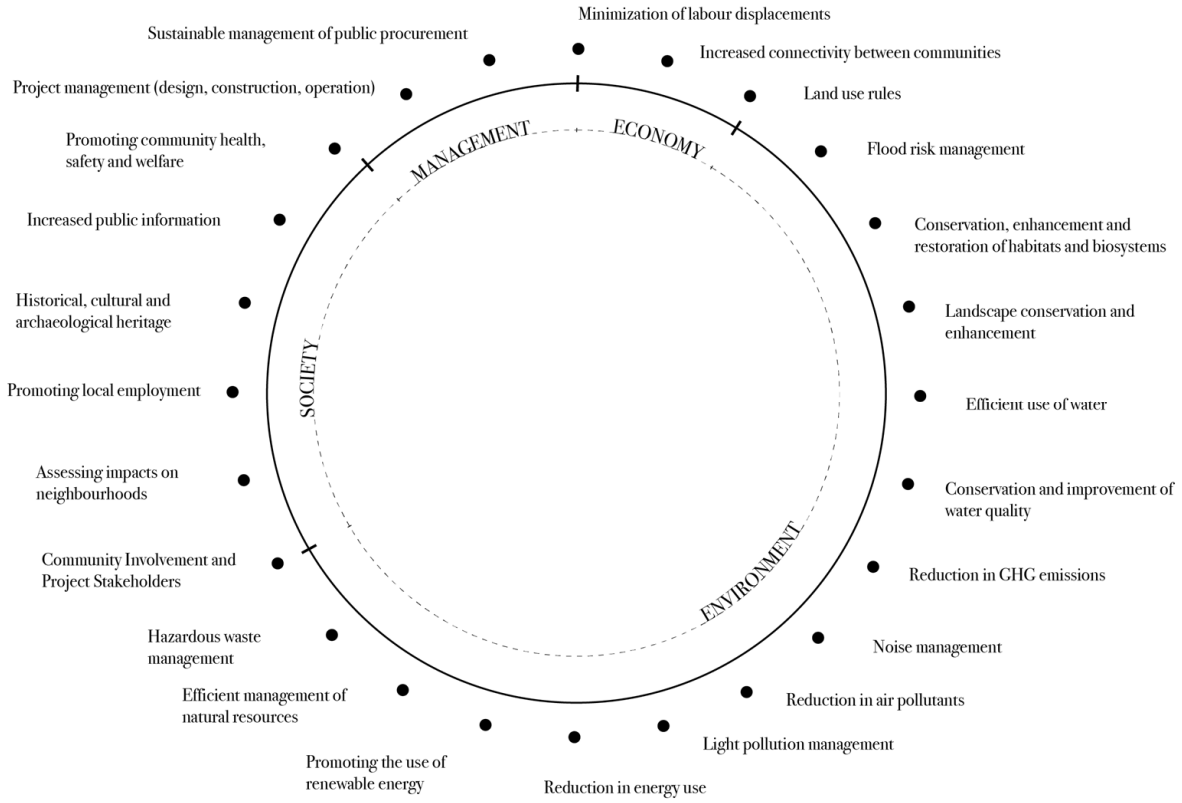


Figure 4. Parameters and aspects of international sustainability certification systems. Own elaboration based on main criteria used in the evaluation of projects by the rating systems of [37].

4. Analysis

4.1. Identification of Multilateral Organizations: Criteria to Be Benchmarked

Even though, according to the latest classification of MDBs, there are 25 organizations of a development banking nature [10], the focus and research was on analyzing the organizations that could cover each one of the parameters defined in the following list of variables.

(a) The MDB has a global or regional scope.
(b) The guidelines of the organization's mandates include the promotion of sustainable economic development and the support of regional cooperation.
(c) The organization's credit rating is AAA.
(d) The financial instruments with which the organization's finance infrastructure projects include loans, lines of credit, and technical assistance during the design and implementation phase of projects.
(e) The organization invests more than 40% of its total disbursements in infrastructure development and specifically in transport, energy, and communications, according to the sectoral breakdown of MDB disbursements concessional and non-concessional, 2015. (See Table 2).

Table 2. Selected variables covered by analyzed MDBs. Own elaboration.

	Variables				
MDB	**a**	**b**	**c**	**d**	**e**
Asian Development Bank (ADB)	Regional	●	●	●	●
African Development Bank [47]	Regional	●	●	●	●
Asian Infrastructure Investment Bank (AIIB)	Regional	●	●	●	–
Inter-American Development Bank (IDB)	Regional	●	●	●	–
European Bank for Reconstruction and Development (EBRD)	Regional	●	●	●	●
International Finance Corporation (IFC)	Regional	●	–	●	–
World Bank (WB)	Global	●	–	●	–

Data extracted from "Guide to Multilateral Development Banks 2018". ● = Complies; – = Not compliant, partially compliant, or no published data.

4.2. Selection of Bodies to Be Analyzed

We analyzed seven international organizations and, after the process of analysis based on the variables set out above, we determined that the number of entities that fully complied with the variables was four.

The following Table 3 shows the analyzed entities as well as the documentation relating to the safeguards included in the object of study.

Table 3. MDBs selected for assessment.

Org	**Date ESG First Established**	**Current ESG Safeguard Policies**	**Date of Entry**	**No. of Documents**	**No. of Words**
ADB	Mid-1990s–early 2000s	Safeguard Policy Statement SPS	2009	1	40,949
AFDB	Mid-1990s	Integrated Safeguards System ISS	2013	1	26,432
IDB	Mid-1990s	Environment and Safeguards Compliance Policy ESCP	2016	6	25,294
EBRD	1991	Environmental and Social Policy ESP	2014	1	33,573

4.3. Identification of Codes, Subcodes, and Reference Indicators in ESG Safeguards

Once we had selected the entities as well as the documents that made up their safeguards, as shown in Table 3 above, we defined the indicators that characterized each of the codes and subcodes of the safeguards. In this process, we were guided by the areas proposed by the guide [10], which reflects that these areas were those that were

most commonly found in a standardized manner in practically all safeguard policies, regardless of the document in which they were found and whether they were explicitly or implicitly defined.

As can be seen in the following Table 4, these thematic areas were grouped according to the three axes of [10]—the backbone of ESG safeguards—which is environment, society, and governance. This table shows the six subcodes into which the environmental thematic area was divided; the ten that applied to the social area, this being the one that contributed most to this classification; and, finally, the six that made up the governance area, as indicated in the study [10].

Table 4. ESG safeguard codes and subcodes. Own elaboration.

Codes	No.	Subcodes—OVE 2018 Thematic Areas
ENVIRONMENT	MA.1	PREVENTION OF AND REDUCTION IN POLLUTION
	MA.2	WASTE/HAZARDOUS MATERIALS, INCLUDING PESTICIDE MANAGEMENT
	MA.3	RESOURCE EFFICIENCY
	MA.4	BIODIVERSITY, NATURAL HABITATS
	MA.4	NATURAL DISASTERS
	MA.5	CLIMATE CHANGE, INCL. GREENHOUSE GAS (GHG) EMISSIONS
	MA.6	TRANSBOUNDARY ISSUES
SOCIAL	S.1	INDIGENOUS PEOPLES
	S.2	FREE, PRIOR AND INFORMED CONSENT OF INDIGENOUS PEOPLES
	S.3	INVOLUNTARY RESETTLEMENT (PHYSICAL DISPLACEMENT)
	S.4	ECONOMIC DISPLACEMENT (INCLUDING LOSS OF RESOURCES/LAND USE)
	S.5	VULNERABLE GROUPS
	S.6	GENDER
	S.7	LABOUR AND WORKING CONDITIONS
	S.8	COMMUNITY HEALTH AND SAFETY
	S.9	SECURITY PERSONNEL
	S.10	CULTURAL HERITAGE (TANGIBLE AND INTANGIBLE)
GOVERNANCE	G.1	ENVIRONMENTAL ASSESSMENT
	G.2	SOCIAL ASSESSMENT
	G.3	STAKEHOLDER CONSULTATION AND PARTICIPATION
	G.4	GRIEVANCE MECHANISM
	G.5	ENVIRONMENTAL AND SOCIAL PERFORMANCE REPORTING BY BORROWER
	G.6	REFERENCE TO THE INSTITUTION'S ACCOUNTABILITY MECHANISM

4.4. Identifying Sustainability Tools as a Reference for Analysis

The focus of the research was on the mapping and detailed analysis of existing sustainability measurement and reporting methods in the market. Although there are hundreds of sustainability measurement systems in use around the world, ranging from simple spreadsheet-based approaches to cloud-based systems, the selection of the two systems to be analyzed was based on the fulfillment of four criteria:

- A generalist scope for all types of infrastructures;
- International recognition;
- Widely used, global systems;
- Accessibility to documentation and datasets to allow for detailed analyses.
- From the above variables, the certificates included in Table 5 below were included.

Taking as a reference the variables previously determined as a starting point for selecting the rating systems and the information in Table 5, two of the three proposed systems were identified due to the ease of obtaining the reference documentation and its availability in the various sources consulted. For this reason, the analysis focused on the following systems, as shown in Table 6 below.

Table 5. Sustainable infrastructure rating tools: main features. Own elaboration.

Rating Tool	ENVISION	CEEQUAL	Infrastructure Sustainability
Launch of the first version of the tool	2012	2003	2012
Country of origin	USA	United Kingdom	Australia
Life cycle phases covered by the tool	Planning and design	Planning and design	Design, construction, and operations
Sustainability issues addressed	1. Quality of life 2. Leadership 3. Resource allocation 4. The natural world 5. Climate change and risk	1. Pollution 2. Land use and ecology 3. Resources 4. Transport 5. Communities and stakeholders 6. Management 7. Resilience 8. Landscape and historic environment	1. Management and governance 2. Resource use, materials, and waste 3. Ecology 4. People and places 5. Innovation
Categories	5	8	5
Subcategories	14	30	15
Certificate levels	-Platinum -Gold -Silver -Bronze	-Excellent -Very good -Good -Pass	-Leader -Excellent -Recommended
Version used for analysis	3	6	2.1
Open data accessibility	YES	NO	NO

Table 6. Sustainable infrastructure rating tools selected.

System	Version	Year of Publication	No. of Words
ENVISIÓN	V.3	2018	91,328
CEEQUAL	V.6	2020	67,680

4.5. Identification of Codes, Subcodes, and Reference Indicators of the Selected Systems

The indicators identified for each primary code (theme) and subcode (subtheme) and the number of indicators of the two systems to be compared are illustrated in Table 7 below. A more detailed explanation of the indicators used is available upon request.

Table 7. CEEQUAL and ENVISION codes, subcodes, and indicators. Own elaboration.

System	Code	No.	Subcode	No. of Indicators
CEEQUAL	MANAGEMENT	1.1	SUSTAINABILITY LEADERSHIP	8
		1.2	ENVIRONMENTAL MANAGEMENT	8
		1.3	RESPONSIBLE CONSTRUCTION MANAGEMENT	3
		1.4	SOCIAL GOVERNANCE OF STAFF AND THE SUPPLY CHAIN	4
		1.5	WHOLE-LIFE COSTING	1
	RESILIENCE	2.1	RISK ASSESSMENT AND MITIGATION	4
		2.2	FLOODING AND SURFACE WATER RUN-OFF	3
		2.3	FUTURE NEEDS	2

Table 7. *Cont.*

System	Code	No.	Subcode	No. of Indicators
CEEQUAL	COMMUNITIES AND STAKEHOLDERS	3.1	CONSULTATION AND ENGAGEMENT	13
		3.2	WIDER SOCIAL BENEFITS	6
		3.3	WIDER ECONOMIC BENEFITS	3
	LAND USE AND ECOLOGY	4.1	LAND USE AND LAND VALUE	8
		4.2	LAND CONTAMINATION AND REMEDIATION	4
		4.3	BIODIVERSITY PROTECTION	6
		4.4	BIODIVERSITY CHANGE AND ENHANCEMENT	4
		4.5	LONG-TERM MANAGEMENT OF BIODIVERSITY	2
	LANDSCAPE AND HISTORIC ENVIRONMENT	5.1	LANDSCAPE AND VISUAL IMPACTS	7
		5.2	HERITAGE ASSETS	5
	POLLUTION	6.1	WATER POLLUTION	5
		6.2	AIR, NOISE, AND LIGHT POLLUTION	8
	RESOURCES	7.1	RESOURCE EFFICIENCY STRATEGY	3
		7.2	REDUCTION IN CARBON EMISSIONS OVER A LIFETIME	4
		7.3	ENVIRONMENTAL IMPACT OF CONSTRUCTION PRODUCTS	3
		7.4	CIRCULAR USE OF CONSTRUCTION PRODUCTS	6
		7.5	RESPONSIBLE SOURCING OF CONSTRUCTION PRODUCTS	6
		7.6	CONSTRUCTION WASTE MANAGEMENT	5
		7.7	ENERGY USE	4
		7.8	WATER USE	7
	TRANSPORT	8.1	TRANSPORT NETWORKS	5
		8.2	CONSTRUCTION LOGISTICS	5
ENVISION	QUALITY OF LIFE	QL1.	WELFARE	6
		QL.2	MOBILITY	3
		QL.3	COMMUNITY	4
	LEADERSHIP	LD.1	COLLABORATION	4
		LD.2	PLANNING	5
		LD.3	ECONOMICS	6
	RESOURCE ALLOCATION	RA.1	MATERIALS	5
		RA.2	ENERGY	4
		RA.3	WATER	4
	NATURAL WORLD	NW1	SITE	5
		NW2	CONSERVATION	6
		NW3	ECOLOGY	6
	CLIMATE AND RESILIENCE	CR.1	EMISSIONS	3
		CR2.	RESILIENCE	6

4.6. Selection of Methods for Analysis

As presented in Figure 2, two tests were designed and developed to address the research hypothesis. To do this, a number of qualitative methods were used, which are outlined below.

The first technique applied was the use of a high-level matrix mapping methodology that compared the ESG categories of the safeguards of each of the MDBs with the subject matter analyzed using the two systems. The full data and analytical matrices and data records are available from the authors upon request as space is limited in this article and, therefore, only high-level summaries are included.

The second method used was a qualitative textual data mining/analysis technique to identify patterns of intertextual co-occurrence of significance [48]. Both methods used the framework of thematic areas covered by multilateral development bank safeguard policy frameworks [10] to structure and prioritize topics of value for analysis.

4.6.1. High-Level Analytical Matrix Linking the Safeguard Areas

The method for constructing high-level associations between the areas covered by the safeguards and the ENVISION and CEEQUAL materiality themes was a simplified and adapted version of the "ecosystem services matrix" [49]. This approach involves the construction of a tabular format to test the strength of linkages across three dimensions and then uses expert panels to test the strength of connection points. This part of the test was limited to the authors' input, so more experts would have been required to further stabilize the results.

The high-level matrix evaluation team assigned scores to a total of 219 indicators, broken down into 67 for ENVISION (spread over the 5 codes and 14 sub-codes) and 152 for CEEQUAL (spread over the 8 codes and 29 sub-codes), defined in Table 7, applying the following scoring scheme:

- Fully Covered (1 point): 1 point was assigned to the indicators of the certification systems that were fully aligned with the objectives and approaches of the subject areas that integrated the different safeguards policies defined in Figure 3. An indicator with this score indicated full and aligned integration with the safeguard.
- Partially Covered (0.5 points): 0.5 points were assigned to indicators that met some, but not all, of the objectives of the thematic area. An indicator in this category indicated that, although partly recognized and addressed, there is still room for more comprehensive coverage.
- Not Covered (0 points): This was assigned to indicators without any focus or content in the safeguards thematic areas. An indicator with a score of zero highlighted opportunities to incorporate new elements in future revisions of certification systems.

However, the technique was used to build an initial composite measure, such as identifying key indicator areas and primary "co-occurrence points" in the samples that could be used in the second phase with the qualitative analysis methodology.

4.6.2. Detailed Text Mining Analysis to Establish the Links between CEEQUAL, ENVISION, and ESG Safeguards

The method chosen for the detailed analysis was qualitative textual text mining analysis. With advances in software solutions, text mining is used as a methodology for social scientists in supporting text analysis as it offers the ability to manage and quantify huge amounts of data over a very short time. It is used in academic disciplines such as economics [50], political science [51], and sociology [52]. The specific technique used for this study was code, subcode, and indicator recognition, which provided a statistical technique for capturing "indicator" keywords within the content analysis [53]. This required a coding framework that was constructed from the three thematic areas of the ESG safeguards, the five ENVISION credits, and the eight CEEQUAL credits.

The coding of the documents was carried out based on the indicators that best identified the thematic area of each of the measurement systems and were identified and selected by the authors of this article.

The advanced technique of keyword comparison between texts was first defined by the philosopher and historian Foucault (1973) [48], who identified intertextual patterns that could determine the answers to social science questions. To identify intertextual patterns, text mining requires a series of social science questions and a hierarchy model or "tree map", which, in this case, used the framework of ESG safeguard areas to link key information codes to the specific subcodes and indicators that were associated with these areas.

The qualitative analysis of the words was made possible by a specialized software tool, "atlas ti", qualitative data analysis software that allows for the rapid analysis of large amounts of data.

An objective was that the qualitative research or analysis conducted with the second technique would validate the high-level analytical matrix of the first analysis, providing evidence as to how the ESG safeguards integrate the different subject matter or control credits of the systems used to measure sustainability. The aim of test two was to determine

the degree of semantic or qualitative co-occurrence and which credits were most integrated into these ESG safeguard systems.

5. Results

5.1. High-Level Matrix Results

By applying the high-level matrix defined in the previous point, we obtained a data matrix large enough to be consolidated as an attached document in point 10 of the appendix of this article. The first results obtained are shown in the following summary Table 8, which illustrates the detailed scores from the high-level matrix by areas and credits, providing an in-depth view of how each bank or financial institution handles the various credits within their ESG safeguard policies.

Table 8. High-level matrix scores by areas and credits.

	ADB			IDB			EBRD			AFDB		
ENVISION	**E**	**S**	**G**	**E**	**S**	**G**	**E**	**S**	**G**	**E**	**S**	**G**
QUALITY	12	24.5	5	12	12.5	3.5	9	31	5	6	21	4
LEADERSHIP	1.5	16.5	15	1.5	9	11	1.5	20	16	1.5	17	13
RESOURCE ALLOCATION	12.5	1.5	1	12.5	0	1	12.5	3	1	12.5	2	1
NATURAL WORLD	19	0	1	19	0	1	19	0	1	19	0	1
CLIMATE AND RISK	8	1	8	12	1	6.5	12	0.5	8	12	0	8
	ADB			**IDB**			**EBRD**			**AFDB**		
CEEQUAL	**E**	**S**	**G**	**E**	**S**	**G**	**E**	**S**	**G**	**E**	**S**	**G**
MANAGEMENT	47.5	13	41	46.5	2.5	30	49	20	41	46	16.5	33
RESILIENCE	26	0	0	29.5	0	0	32.5	0	0	32.5	0	0
COMMUNITIES AND STAKEHOLDERS	0	97	38.5	0	43.5	36	0	81.5	38.5	0	73.5	36.5
LAND USE AND ECOLOGY	57	0	3	54.5	0	0	59.5	0	3	57	0	0
LANDSCAPE AND HISTORIC ENVIRONMENT	5.5	23.5	39.5	5.5	21	30	5.5	37	39.5	5	37	35.5
POLLUTION	31.5	5	34	31.5	5	18	31.5	5	34	26.5	5	26
RESOURCES	60	5.5	20	57	4	17	60	3	20	60	3	20
TRANSPORT	7	19	34	7	7	10	7	9	34	0	9	34

The visual representation provided by the heatmap serves as an analytical tool, offering an immediate, intuitive grasp of the comparative performance of the institutions under consideration—namely ADB, IDB, EBRD, and AFDB—across a spectrum of environmental and governance parameters. This visual format utilizes a color gradient to symbolize the range of scores, with darker hues corresponding to higher scores and lighter ones to lower scores, creating a visually stratified assessment.

On the basis of the average values shown in Table 9, the safeguards were better adapted to the ENVISION certification system than to that of CEEQUAL with regard to the environmental themes, where a difference of 2.2% was reached. This was in contrast to the themes in the area of governance or processes, where the safeguards were better adapted to CEEQUAL, reaching a difference of 10.48%, which was very significant. Finally, it was again in the social area where the safeguards demonstrated a greater adaptation to the ENVISION credits, with a difference of 8.22% from CEEQUAL. As discussed in the previous paragraph in relation to the results achieved, Table 9 below presents a percentage summary of the results obtained through the high-level matrix analysis, illustrating how the sustainability certification credits were distributed among the ESG thematic areas (environmental, social, and governance) in each assessed institution.

Table 9. Distribution of credits of the certification systems by ESG safeguard area. Own elaboration.

	ENVISION	CEEQUAL
ENVIRONMENTAL	44.86%	42.60%
SOCIAL	32.33%	24.11%
GOVERNANCE	22.81%	33.30%
Total	100.00%	100.00%

Table 10 shows the percentage distribution of credits of the certification systems in each of the thematic areas of the safeguards, detailed in each financial institution previously selected.

Table 10. High-level matrix total scores. Own elaboration.

		Integration of Safeguard System Credits			
ENVISION		**ADB**	**IDB**	**EBRD**	**AFDB**
QUALITY OF LIFE		41.50	28.00	45.00	31.00
LEADERSHIP		33.00	21.50	37.50	31.50
RESOURCE ALLOCATION		15.00	13.50	16.50	15.50
NATURAL WORLD		20.00	20.00	20.00	20.00
CLIMATE AND RISK		17.00	19.50	20.50	20.00
	TOTAL	126.50	102.50	139.50	118.00
CEEQUAL		**ADB**	**IDB**	**EBRD**	**AFDB**
MANAGEMENT		101.50	79.00	110.00	95.50
RESILIENCE		26.00	29.50	32.50	32.50
COMMUNITIES AND STAKEHOLDERS		135.50	79.50	120.00	110.00
LAND USE AND ECOLOGY		60.00	54.50	62.50	57.00
LANDSCAPE AND HISTORIC ENVIRONMENT		68.50	56.50	82.00	77.50
POLLUTION		70.50	54.50	70.50	57.50
RESOURCES		85.50	78.00	83.00	83.00
TRANSPORT		60.00	24.00	50.00	43.00
	TOTAL	607.50	455.50	610.50	556.00

Table 10 below shows the points achieved by the safeguards, per credit, for each of the ENVISON and CEEQUAL systems, as well as the final totals.

The area chart in Figure 5 below shows the degree of adoption of safeguards with respect to the credits of the two systems considered. The upper part of the figure compares the relationship of safeguards with ENVISION and the lower part with CEEQUAL.

As can be seen in Figure 5 above, the safeguard policies presented a polygonal adaptation area for ENVISION credits with different densities but with certain common results. The credit that was least integrated into all safeguards was "Climate and Risk" as it was in the range of [17;20.5] points. Credits such as "Resource Allocation" and "Natural World" were also poorly covered by the safeguards, reaching ranges of [13;15] points and [20] points, respectively. It is graphically noticeable that the credit with the highest uptake in safeguard policies was "Quality of Life", with a range of [28;45] points. Finally, the "Leadership" credit was more stably integrated by most of the organizations analyzed, with a score of [31.5;37.5], except for the IDB safeguard, which barely reached [21.5] points. By way of summary, it can be argued that the safeguard policies that were best adapted to the ENVISION system were those of ADB and EBRD, although, in some credits, they had very low scores; the IDB safeguard policy had the worst adaptability, with low points totals for all the credits of both systems.

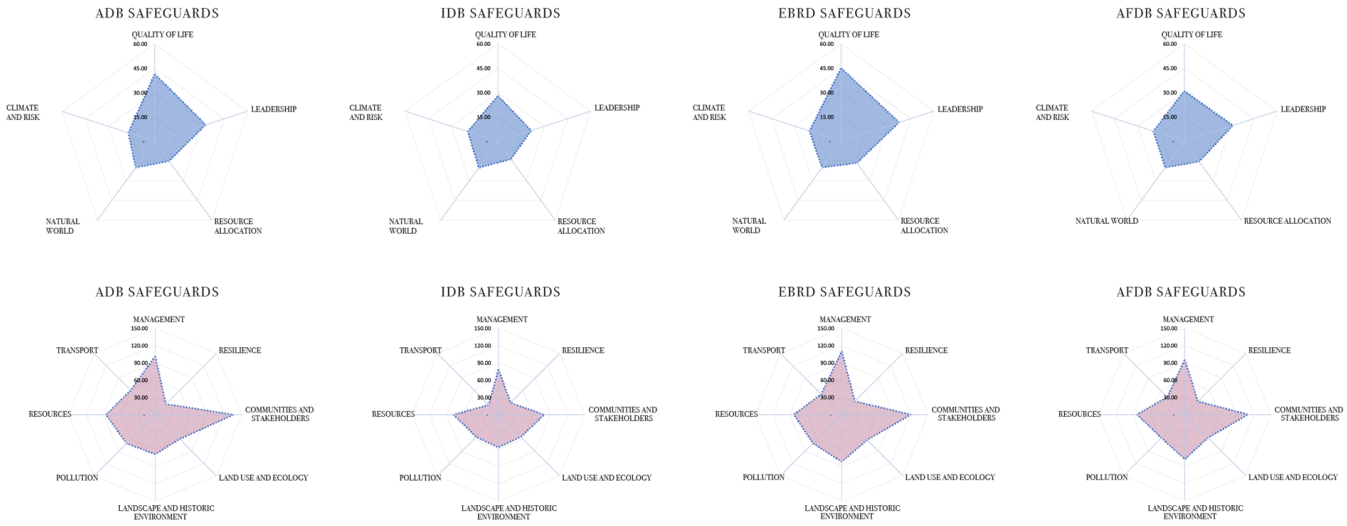


Figure 5. Distribution of ENVISION and CEEQUAL credits across MDB ESG safeguards. Own elaboration.

Regarding the ENVISION analysis and the results obtained, it can be argued that the EBRD safeguard led with the "Quality of Life" credit, which suggests a much stronger focus than the rest of the banks on improving quality of life through specific areas such as pollution prevention and reduction; the protection of communities within "cross-border projects", "indigenous peoples", "informed consent and processes", and "grievance and consultation mechanisms"; and in general aspects much more linked to insurance and working conditions. As for the "Leadership" credit, both the EBRD and ADB safeguards again stood out from the rest, showing strong leadership skills in their implementation, especially on issues related to "community planning and long-term monitoring", with a focus on projects throughout their life cycle, which, according to the results, was articulated in the social and governance thematic areas. From the results obtained for the "Resource Allocation" credit, all the safeguards showed very low scores due to the fact that the environmental thematic area did not include the materiality that ENVISION considers important to control, such as "Reducing water consumption during construction and operation". This is probably due to the fact that the safeguards are not very operational, as has already been mentioned.

Regarding the results assessed within the "Natural World" credit, all the safeguards also presented low and equal scores and, furthermore, they were all integrated in an integral manner only in the thematic areas with an environmental focus, achieving particular results in issues such as "land use", "soil quality", and the "control of wastewater and biodiversity". Finally, regarding the "Climate and Risk" credit, scores appeared very even across all safeguards, suggesting a very homogeneous approach among all safeguards in climate risk mitigation and that they did not adequately integrate issues such as "Climate change assessment, "Greenhouse gas reduction and assessing the vulnerability of projects with respect to their sustainable future".

In the case of the CEEQUAL system, all the graphs show a less compact area, with more peaks of variation between credits; this is because at least three of the credits studied obtained very low scores. These were "Transport", with the IDB safeguard scoring the lowest, with only 24; "Resilience"; and "Land Use and Ecology", also with the lowest score for IDB policies. The three credits "Resources", "Management", and "Communities and Stakeholders" scored high in all the safeguards analyzed, with ADB scoring the highest, with a difference of [63.5] points. The "Pollution and Landscape" and "Historic Environment" credits had high score ranges, with [54.5;70] and [56.5;82], respectively. In summary, it can be said that the safeguard policies that were best adapted to the CEEQUAL system were those of ADB and EBRD, although, for some credits, they had very low scores,

and the IDB safeguard policy had the worst adaptability, with low points totals for all the credits, far below the other three safeguard policies.

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With respect to the CEEQUAL analysis and the results obtained, for the "Management" credit, the EBRD and ADB safeguards showed high scores, suggesting strong management in their safeguards in areas such as "Environmental Management" and "Sustainability Leadership", which were highly integrated into the specific environmental and governance areas of the safeguards.

For the "Resilience" credit, the scores of the different safeguards were the most even and the lowest of all the credits analyzed. The EBRD and AFDB safeguards led slightly, indicating that these two banks value resilience in a similar way by integrating issues such as "Risk assessment and mitigation" and "Floods and surface water runoff" specifically in the environmental thematic area. The "Communities and Stakeholders" credit was one of the most integrated across the safeguards and here the ABS safeguard in particular led, showing a strong focus on the inclusion of specific issues such as "Consultation and Engagement" and "Broader Social and Economic Benefits", integrating into social areas on issues such as "Indigenous Peoples", "Free, Prior and Informed Consent by Indigenous Peoples", "Economic Displacement (Including Loss of Resource/Land Use)".

Accordingly, the specific credits of "Land Use and Ecology" and "Landscape and Historic Environment" scores varied, but with EBRD safeguards leading slightly. This is because although all safeguards had scores for "Land Use and Land Value", "Land Pollution and Land Use", "Land Use and Ecology", "Landscape and Historic Environment", "Land Contamination and Land Reclamation", and "Biodiversity Protection", but the EBRD safeguard integrated many more issues, such as "Biodiversity Change and Enhancement". Regarding the scores obtained for "Heritage", all safeguards had a very good consideration of these elements, and specific documents for the control of this area were integrated into all of them. The "Pollution" credit was an important issue that all safeguards incorporated in their environmental thematic areas such as "Pollution Prevention and Abatement", with high scores for elements such as "Water and soil pollution" and "Noise and landscape pollution".

Regarding the credit "Resources", the scores were high and even, integrating mainly in themes such as "Environmental Impact of Construction Products" and "Construction Waste Management", integrated into the environmental and governance thematic areas, specifically in the thematic areas of "Resource Efficiency" and "Hazardous waste/materials, including pesticide management". To finish, the credit "Transport" appeared with inconsistent scores across safeguards and was most covered by ADB safeguards followed by the EBDR. Topics such as "Construction logistics", "Minimizing construction traffic disruptions", "Movement of construction materials", and "Movement of construction materials" were poorly incorporated in all the safeguards and only appeared in the thematic area of "Governance" in the theme of "Environmental assessment", as reflected in the scores achieved. This can be interpreted as a safeguards approach that was not aligned with practices in this area during project construction.

In conclusion and as discussed above, the safeguards policies of multilateral banks and sustainability certification schemes such as CEEQUAL and ENVISION have related purposes but are applied in different ways and this is reflected in the results obtained from the high-level matrix assessment.

5.2. Qualitative Analysis Results

As defined in the previous section, the tool used to carry out the qualitative analysis showed the degree of co-occurrence between the thematic areas that managed the safeguard policies and the credits that integrated the two selected sustainability certification tools. The degree of integration of the selected indicators defining these tools in the safeguards was therefore obtained in detail.

5.2.1. ENVISION Co-Occurrences

The results obtained in the case of ENVISION, highlighted in the following Table 11, show that in practically all the safeguards, the most integrated credit was "Climate and Resilience", with a single exception, that of the ABS safeguard policy, where the highest was "Quality of Life", with an average value of [0.5225]. With respect to the average number of co-occurrences, the lowest was the "Natural Word" credit, with [0.099]. None of the safeguards presented co-occurrences higher than the average in all the credits; only the ABS and EBRD policies were higher in four of the five credits, this not being fulfilled for the "Natural World" credit for EBRD or "Resource Allocation" for ABS. The lowest co-occurrence was found for the "Quality of Life" credit in the IDB policy, for which a score of [0.022] was reached—almost a 0.080 difference with respect to the average achieved by the four safeguards. On the other hand, the highest co-occurrence score was achieved by the ABS safeguard in the "Climate and Resilience" credit, with [0.7396], almost 0.22 above the average.

Table 11. Results of co-occurrence for ENVISION. Own elaboration.

		Climate and Resilience Gr = 23	**Leadership Gr = 49**	**Natural World Gr = 14**	**Quality of Life Gr = 17**	**Resource Allocation Gr = 9**	**Totals**
		Coefficient	**Coefficient**	**Coefficient**	**Coefficient**	**Coefficient**	
ADB	Environmental Gr = 30	0.7097	0.0260	0.1000	0.1750	0.1143	1.124937
	Governance Gr = 54	0.0267	0.1075	0.0149	0.0290	0.0000	0.178105
	Social Gr = 284	0.0033	0.0605	0.0068	0.0203	0.0000	0.090874
	Totals	0.7396	0.1940	0.1217	0.2243	0.1143	
		Climate and Resilience Gr = 16	**Leadership Gr = 91**	**Natural World Gr = 20**	**Quality of Life Gr = 11**	**Resource Allocation Gr = 21**	**Totals**
		Coefficient	**Coefficient**	**Coefficient**	**Coefficient**	**Coefficient**	
IDB	Environmental Gr = 41	0.2955	0.0313	0.1509	0.0196	0.1273	0.624529
	Governance Gr = 6	0.0000	0.0319	0.0000	0.0000	0.0385	0.070377
	Social Gr = 723	0.0027	0.0436	0.0054	0.0027	0.0040	0.058498
	Totals	0.2982	0.1068	0.1564	0.0223	0.1698	

Table 11. *Cont.*

		Climate and Resilience Gr = 39	Leadership Gr = 96	Natural World Gr = 13	Quality of Life Gr = 23	Resource Allocation Gr = 22	Totals
		Coefficient	**Coefficient**	**Coefficient**	**Coefficient**	**Coefficient**	
EBRD	Environmental Gr = 62	0.6290	0.0128	0.0563	0.0241	0.2727	0.995014
	Governance Gr = 29	0.0000	0.1062	0.0000	0.0196	0.0000	0.125803
	Social Gr = 204	0.0167	0.0638	0.0000	0.0657	0.0000	0.146294
	Totals	0.6458	0.1828	0.0563	0.1094	0.2727	
		Climate and Resilience Gr = 31	**Leadership Gr = 34**	**Natural World Gr = 16**	**Quality of Life Gr = 15**	**Resource Allocation Gr = 24**	**Totals**
		Coefficient	**Coefficient**	**Coefficient**	**Coefficient**	**Coefficient**	
AFDB	Environmental Gr = 72	0.3919	0.0095	0.0602	0.0357	0.1707	0.668103
	Governance Gr = 14	0.0000	0.0909	0.0000	0.0000	0.0000	0.090909
	Social Gr = 177	0.0146	0.0657	0.0052	0.0159	0.0101	0.111422
	Totals	0.4065	0.1661	0.0654	0.0516	0.1808	

Finally, the results of total co-occurrences for each safeguard were obtained, as can be seen in the following Table 12. The highest co-occurrence was obtained for ADB and EBRD, with a difference of [0.64] between them, and with respect to those of IDB and AfDB, reaching a difference with respect to their totals of [0.09].

Table 12. Summary of co-occurrence scores of ENVISION with MDB ESG safeguard areas. Own elaboration.

	ADB	IDB	EBRD	AFDB	Average
ENVIRONMENT	1.1249	0.625	0.9950	0.6681	0.85315
GOVERNANCE	0.1781	0.070	0.1258	0.0909	0.11630
SOCIAL	0.0909	0.058	0.1463	0.1114	0.10177
Totals	1.3939	0.7534	1.2671	0.8704	

In the following Table 13, we observe the same results presented in Table 12 but based on ENVISION credits.

Table 13. Summary of co-occurrence scores of MDB ESG safeguard areas with ENVISON credits. Own elaboration.

	ADB	IDB	EBRD	AFDB	Average
CLIMATE AND RESILIENCE	0.7396	0.2982	0.6458	0.4065	0.5225
LEADERSHIP	0.1940	0.1068	0.1828	0.1661	0.1624
NATURAL WORLD	0.1217	0.1564	0.0563	0.0654	0.1000
QUALITY OF LIFE	0.2243	0.0223	0.1094	0.0516	0.1019
RESOURCE ALLOCATION	0.1143	0.1698	0.2727	0.1808	0.1844
Totals	1.3939	0.7534	1.2671	0.8704	

As we had highlighted previously the visual representation provided by the heatmap serves as an analytical tool, offering an immediate, intuitive grasp of the comparative performance of the institutions under consideration—namely ADB, IDB, EBRD, and AFDB—across a spectrum of environmental and governance parameters. This visual format utilizes a color gradient to symbolize the range of scores, with darker hues corresponding to higher scores and lighter ones to lower scores, creating a visually stratified assessment.

The Sankey graphs included in Figure 6 clearly exhibit that the thematic areas most connected with the ENVISION credits were the environmental and social areas, with the area associated with governance or processes being far behind. This last area was integrated in very few credits: only in the ADB safeguard policy, for which it was integrated with very low co-occurrences in four of the five credits, with "Resource Allocation" not covered. In the case of EBRD, it was found only in two credits, "Leadership" and "Quality of Life", and, finally, for IDB and AfDB, it was only found for the "Leadership" credit, with a very low co-occurrence.

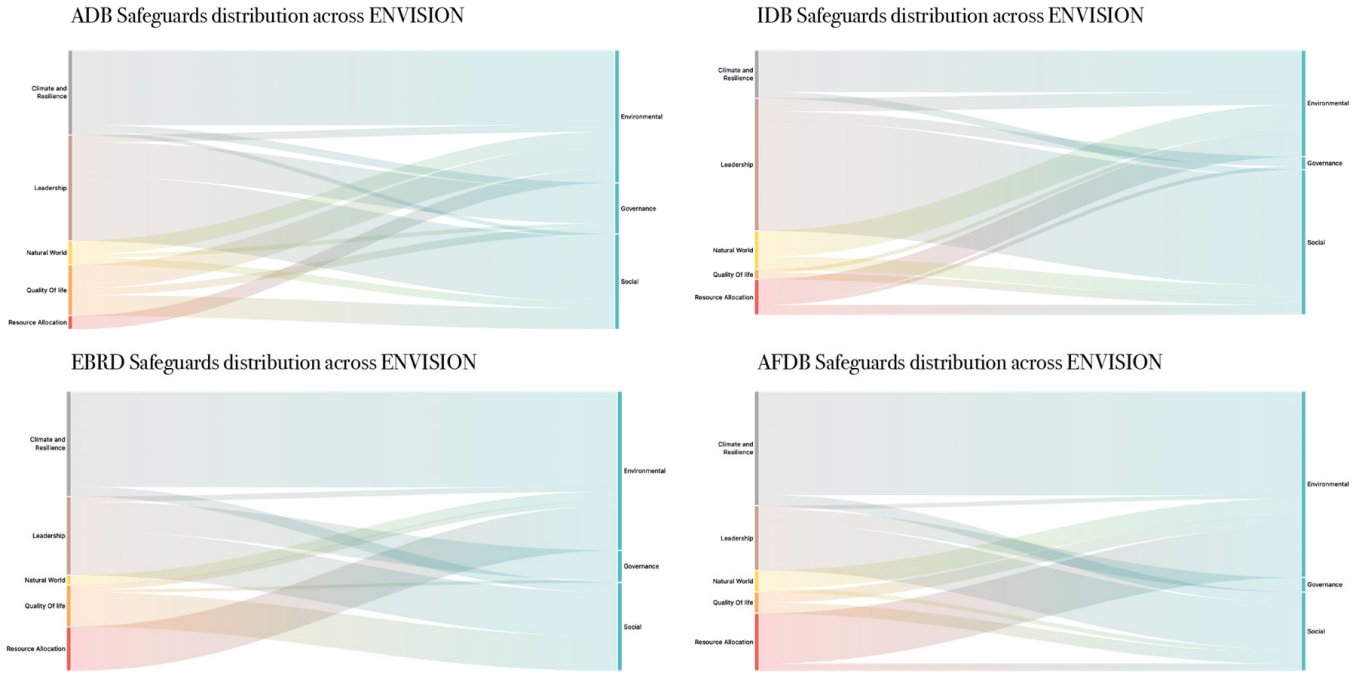


Figure 6. Sankey charts with distribution of ENVISION credits in thematic areas of safeguards according to qualitative analysis.

To recap and summarize in the case of ENVISION, integrating the areas contained in the parameters included in the "Quality of Life" credit would provide projects with more insight into aspects that, a priori, seem reasonable for the safeguards to include. Examples are addressing the impact on the health of the communities and inhabitants of the communities affected by or hosting the infrastructure as well as aspects important to control during the execution of projects, such as the physical safety of residents and workers and the mitigation of impacts and nuisances during construction. In addition, the low adoption of these credits in the scope of the safeguards analyzed can affect the functionality of the infrastructure, something that undoubtedly impacts the environment and above all the sensitivity of the community affected by the infrastructure. Finally, the low adoption of the parameters defined by the "Natural World" credit, such as the biodiversity of the site, as well as soil and water, considerably affects the conservation of areas with high diversity or ecological value and the safeguarding of surface water regimes and aquifers that may be altered during the construction and operation of an asset. The incorporation of these parameters within safeguard policies is of high importance, as incorporating designs that

consider these control points will allow for very high sustainability values to be achieved at the end of an infrastructure's life cycle.

5.2.2. CEEQUAL Co-Occurrences

The results obtained in the case of CEEQUAL in Table 14 show that in practically all the safeguards, the credit that was most integrated was that of "Communities and Stakeholders", with an average value of 0.6403. The lowest average number of co-occurrences was for "Transport" with 0.0010, where only the IDB safeguard integrated co-occurrences, and no co-occurrences were found in the rest of the safeguards.

Table 14. Results of co-occurrence for CEEQUAL. Own elaboration.

		Management Gr = 31	**Resilience Gr = 29**	**Communities and Stakeholders Gr = 319**	**Land Use and Ecology Gr = 70**	**Landscape and Historic Environment Gr = 14**	**Pollution Gr = 1**	**Resources Gr = 8**	**Transport Gr = 1**	**Totals**
		Coefficient	**Coefficient**	**Coefficient**	**Coefficient**	**Coefficient**	**Coefficient**	**Coefficient**	**Coefficient**	
ADB	Environment Gr = 30	0.0339	0.0351	0.0325	0.1765	0.0233	0.0333	0.1176	0.0000	0.419
	Governance Gr = 72	0.3733	0.0412	0.1171	0.0441	0.0118	0.0000	0.0127	0.0000	0.600
	Social Gr = 284	0.0535	0.0330	0.6210	0.1028	0.0171	0.0000	0.0034	0.0000	0.831
	Totals	0.4607	0.1093	0.7707	0.3234	0.0521	0.0333	0.1337	0.0000	
		Management Gr = 107	**Resilience Gr = 186**	**Communities and Stakeholders Gr = 424**	**Land Use and Ecology Gr = 20**	**Landscape and Historic Environment Gr = 18**	**Pollution Gr = 2**	**Resources Gr = 12**	**Transport Gr = 3**	**Totals**
		Coefficient	**Coefficient**	**Coefficient**	**Coefficient**	**Coefficient**	**Coefficient**	**Coefficient**	**Coefficient**	
IDB	Environment Gr = 41	0.0137	0.0318	0.0109	0.0517	0.0172	0.0488	0.1277	0.0000	0.302
	Governance Gr = 6	0.0089	0.0000	0.0047	0.0000	0.0000	0.0000	0.0000	0.0000	0.014
	Social Gr = 723	0.0285	0.0168	0.5232	0.0068	0.0109	0.0000	0.0068	0.0041	0.597
	Totals	0.0511	0.0486	0.5388	0.0585	0.0282	0.0488	0.1345	0.0041	
		Management Gr = 70	**Resilience Gr = 43**	**Communities and Stakeholders Gr = 340**	**Land use and ecology Gr = 60**	**Landscape and historic environment Gr = 39**	**Pollution Gr = 8**	**Resources Gr = 17**	**Transport Gr = 6**	**Totals**
		Coefficient	**Coefficient**	**Coefficient**	**Coefficient**	**Coefficient**	**Coefficient**	**Coefficient**	**Coefficient**	
EBRD	Environment Gr = 62	0.0476	0.0606	0.0361	0.1193	0.0000	0.0938	0.1970	0.0000	0.554
	Governance Gr = 30	0.4286	0.0282	0.0571	0.0227	0.0000	0.0000	0.0000	0.0000	0.537
	Social Gr = 204	0.0787	0.0466	0.5111	0.0602	0.0385	0.0000	0.0000	0.0000	0.735
	Totals	0.5549	0.1354	0.6043	0.2022	0.0385	0.0938	0.1970	0.0000	
		Management Gr = 65	**Resilience Gr = 27**	**Communities and Stakeholders Gr = 264**	**Land Use and Ecology Gr = 40**	**Landscape and Historic Environment Gr = 25**	**Pollution Gr = 14**	**Resources Gr = 17**	**Transport Gr = 0**	**Totals**
		Coefficient	**Coefficient**	**Coefficient**	**Coefficient**	**Coefficient**	**Coefficient**	**Coefficient**	**Coefficient**	
AFDB	Environment Gr = 72	0.0620	0.0421	0.0633	0.1200	0.0104	0.0886	0.2027	0.0000	0.589
	Governance Gr = 14	0.0533	0.0789	0.0258	0.0000	0.0000	0.0000	0.0000	0.0000	0.158
	Social Gr = 177	0.0568	0.0515	0.5583	0.0284	0.0151	0.0160	0.0052	0.0000	0.731
	Totals	0.1721	0.1726	0.6474	0.1484	0.0255	0.1046	0.2079	0.0000	

None of the safeguards showed higher than average co-occurrences in all credits; only the EBRD policies were higher in six of the eight credits, "Communities and Stakeholders" and "Transport" not being integrated. The lowest co-occurrence was found for the "Landscape and Historic Environment" credit in the AfDB policy, where a score of 0.025 was achieved, but, in any case, it was a very close result to the average achieved by the rest

of the safeguard policies, which was 0.036. On the other hand, the highest co-occurrence score was achieved by the ABS safeguard in the "Communities and Stakeholders" credit, with 0.74066 with a 0.13 difference with respect to the average.

Finally, the results of total co-occurrences for each safeguard were obtained, as can be seen in Table 15, highlighting that the highest co-occurrence was obtained for ADB and EBRD, with a difference of [0.06] between them.

Table 15. Summary of co-occurrence scores of CEEQUAL with MDB ESG safeguard areas. Own elaboration.

	ADB	IDB	EBRD	AFDB	Average
ENVIRONMENT	0.4189	0.3018	0.5543	0.5891	0.4660
GOVERNANCE	0.6003	0.0136	0.5366	0.1581	0.3271
SOCIAL	0.8308	0.5972	0.7352	0.7313	0.7236
Totals	1.8499	0.9126	1.8261	1.4785	

The colour coding of Heat map highlighted on Tables 15 and 16 with the same approach and meaning as mentioned above.

Table 16. Summary of co-occurrence scores MDB ESG safeguard areas with ENVISON credits. Own elaboration.

	ADB	IDB	EBRD	AFDB	Average
MANAGEMENT	0.4607	0.0511	0.5549	0.1721	0.3097
RESILIENCE	0.1093	0.0486	0.1354	0.1726	0.1165
COMMUNITIES AND STAKEHOLDERS	0.7707	0.5388	0.6043	0.6474	0.6403
LAND USE AND ECOLOGY	0.3234	0.0585	0.2022	0.1484	0.1831
LANDSCAPE AND HISTORIC ENVIRONMENT	0.0521	0.0282	0.0385	0.0255	0.0360
POLLUTION	0.0333	0.0488	0.0938	0.1046	0.0701
RESOURCES	0.1337	0.1345	0.1970	0.2079	0.1683
TRANSPORT	0.0000	0.0041	0.0000	0.0000	0.0010
Totals	1.8833	0.9126	1.8261	1.4785	

In the following Table 16, we observe the same results presented in Table 15 but based on CEEQUAL credits.

The Sankey graphs illustrated in Figure 7 show that the thematic areas most connected with CEEQUAL credits were the environmental and social areas, with the area associated with governance or processes being far behind. This last area was integrated in very few credits: only in the safeguard policies of ADB and EBRD, being integrated with co-occurrences in six of the eight credits for ADB and in four of eight for EBRD. The credits not covered in the case of ADB were "Pollution" and "Transport" and in the case of EBRD were "Landscape and Historic Environment", "Pollution", "Resources", and Transport.

To recap and summarize, in the case of the CEEQUAL system, the adoption of "Landscape and Historic Environment", "Pollution", and "Transport" credits in the safeguards analyzed was very low, even in the case of the "Transport" credit. While it is true that the "Transport" area considers the effective management of the impacts of all modes of transport, both during construction and during operation, it also includes the movement of construction materials, the waste generated, and the transport of the construction workforce itself, as well as the disruption of the affected population and users of the transport network during the life of the asset. Therefore, we consider that this is an area that the safeguards should contain within their scope. Regarding the "Landscape and Historic Environment" area, which analyzes the parameters that contribute to the conservation of the landscape and associated heritage elements in and around the project site, the integration of these

parameters in the safeguards analyzed was very low. Such integration will contribute to protecting and enhancing both landscape characteristics and heritage assets where present. This is the case not only from the point of view of the aesthetic value or visual impact of infrastructure in the surrounding environment but also the measures taken to protect and enhance the historic environment for the benefit of present and future generations of the community affected by it. Perhaps most relevant is the low value achieved in the "Pollution credit", the third lowest value achieved in the qualitative analysis. All safeguards analyzed had areas pertaining to pollution prevention and reduction, such as the control of hazardous waste or materials, including the handling of pesticides, but did not contain parameters that allowed for the control of air, water, and noise pollution resulting from the construction and future operation of assets. With such measures, we believe that the approach proposed within the safeguards for pollution control, undoubtedly an important sustainability parameter to control, could be greatly improved.

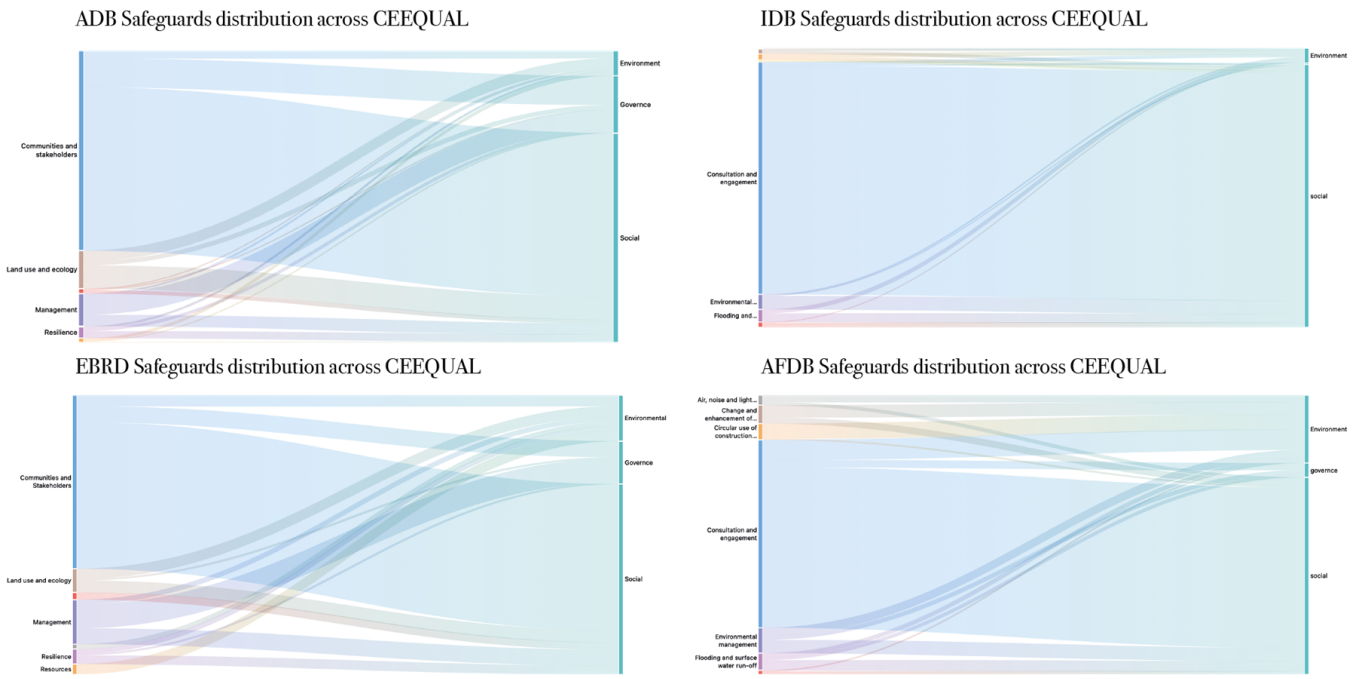


Figure 7. Sankey charts with distribution of CEEQUAL credits in safeguards thematic areas according to qualitative analysis.

6. Conclusions

As we have already said, it should be understood that the ESG safeguards policies employed by MDBs seek to mitigate risks and promote sustainable practices in large-scale projects, generally encompassing high-level concepts of social and environmental issues and governance, while the CEEQUAL and ENVISION schemes promote operational and technical excellence at the project level. This has been a major challenge that has posed several important methodological constraints. Firstly, there was heterogeneity in the sustainability metrics, given that the credits or thematic areas of assessment proposed in the selected ENVISION and CEEQUAL systems and those used by MDBs' ESG safeguards policies had to be aligned, which led to inconsistencies in the interpretation and design of the methodologies used so that the methodologies used resorted to qualitative assessment. Secondly, the identification and selection of codes, sub-codes, and indicators for both certification systems and safeguards had to conform to criteria of applicability and relevance, and, in certain CEEQUAL credits, it was difficult to standardize them. Another challenge we faced was to compile and group all the information from the banks' safeguards, which, in many cases, meant eight or even nine different documents needed to be processed in an integrated way with the software used.

This paper presented a comparative analysis of the extent to which safeguard policies employed by multilateral infrastructure development organizations integrate the sustainability measurement credits or checkpoints proposed in common infrastructure sustainability assessment tools. The aim was to contribute to the overview and debate on whether these safeguard policies cover all aspects of sustainability necessary to comply with international certifications. The proposed comparative framework is mainly based on a combination of two tools with the same approach, consisting of the comparison of ESG areas and the ENVISION and CEEQUAL credits.

Do MDB safeguard policies comply with all the items and indicators monitored in the credits of the international sustainability certificates?

The answer confirmed by the analyzed data (See Supplementary Materials) is that they do not. Both in the results obtained in the high-level matrix and confirmed by the qualitative analysis carried out, there is a clear lack of integration in governance, which can be seen in the very low scores obtained for the credits of the two systems analyzed.

Furthermore, there is a contradiction in the future development of safeguard policies ensuring that all areas of sustainability are guaranteed. On the one hand, there is a demand for approaches to have a more detailed assessment performance tailored to local market sensitivities and infrastructure typology, which means, among other things, that they should be more case- and location-specific. At the same time, there is a demand for these safeguards to be broader so that they are more adaptable to a wide group of users for different case circumstances. There is also a need for these tools to have better-integrated and more standardized areas and to be able to provide more transparent results. In line with some points highlighted by Humphrey [23], we agree that the ESG safeguard approach used by the major multilateral development banks requires a thorough rethink to address conceptual and practical shortcomings.

Can the future development of new safeguard policies respond to the challenges of providing benchmarks and performance indicators, better guidelines, and greater availability of implementation data, and thus be utilized to conduct ex-post analyses of the impacts on infrastructure sustainability? As with the multiple facets of the sustainability concept itself, the development of more comprehensive and integrated safeguards can only happen when all parameters that have an impact during the design and construction phase of the asset are considered, something that is not the case today.

Efforts have been made by multilateral organizations to implement safeguard policies in terms of tools to control the sustainability of the projects they finance, not only for the conceptualization and design phase but also for the subsequent construction phase, as well as emphasizing the care and commitment they require from borrowers to ensure compliance. Despite this, the analysis shows that the tools are limited in scope and do not incorporate important aspects in achieving guarantees for the sustainability of infrastructure. The literature review conducted in this work shows that, although the concept of sustainability has become increasingly important, the ex-post assessment of the sustainability of infrastructure projects remains an unresolved issue, and this is demonstrated even more so if we try to integrate it using international certificate credits and tools. This does not mean that the MDB safeguards are a complete failure—far from it. The safeguards have had a very positive impact, improving the way MDBs design and implement projects, reducing negative social and environmental impacts and repairing them when they occur [17].

The two ENVISION CEEQUAL certificate tools analyzed are biased toward environmental approaches, to the detriment of the more economic and social dimensions [26], the latter being a top priority for multilateral safeguards as well as for developing countries that host the infrastructure financed by these entities and where the promotion of economic growth and sustainable living is a predominant objective when making an investment. This is perhaps the first point to consider in conclusion, as the integration of many of the parameters included in the environmental credits of the two ENVISION and CEEQUAL certificates was not included in the safeguards analyzed, given that the design of these safeguards was mostly not based on the existing legal and regulatory frameworks in the countries

where the projects were located and that they were not able to provide comprehensive environmental requirements and guidelines for the projects.

Consequently, although the current safeguard approaches enable parameters that affect the sustainability of infrastructure to be controlled, none of them can be used to carry out a holistic assessment. However, we note that the considerable work achieved through public policy itself, as well as the accumulated knowledge and experience of the staff managing these ESG safeguards at multilateral development banks, would be extremely valuable in convincing governments of the benefits of a more holistic and comprehensive approach that considers many of the parameters not currently included from the outset. Such an approach could also aid in providing practical assistance and best practice examples to help strengthen the monitoring frameworks of countries hosting infrastructure. Finding a tool that encompasses all the features of international certification schemes for assessing the sustainability of projects would be a complicated issue due to the great difference between the regions or countries in which they would be applied as well as the nature of the projects themselves and the necessary compromise between accuracy and feasibility. This could be achieved by integrating the different documents into a single one, consolidating and standardizing the same areas of action, which could well be the same ESG areas, as well as all the parameters that can be considered in infrastructure projects, or by integrating clear and well-defined indicators, as well as their measurement and comparison methodologies, into the safeguard policies themselves.

Finally, the taxonomy proposed by the EU and the growing environmental pressures in decision-making for the financing of infrastructure projects associated with environmental protection and the prevention of the breakdown of economic and social systems can be considered a perfect impetus for new lines of research that seek to analyze how this taxonomy could be integrated into the current ESG safeguard policies of these multilateral organizations.

To enhance the alignment between public authorities, multilateral banks, and companies holding sustainability certifications like ENVISION or CEEQUAL, a three-phase integration approach is recommended. Initially, a universal taxonomy should be established to align diverse ESG metrics, thematic assessment areas, and indicators, streamlining them into a unified sustainability framework. This would involve the creation of a hybrid certification model that merges high-level policy safeguards with detailed project-level operational criteria, tailored to local contexts yet maintaining global sustainability principles. A subsequent phase would introduce a centralized digital platform for standardized data management, fostering the transparent and consistent application of qualitative and quantitative assessments across various projects. This platform would support the cross-comparison of sustainability parameters and facilitate a more rigorous post-implementation analysis of infrastructure impacts. Lastly, it is essential to refine safeguard policies to balance specificity for local market sensitivities with broad applicability for diverse user groups and scenarios. This includes incorporating overlooked ESG aspects into all project phases, particularly governance, and leveraging the expertise of MDBs to strengthen host countries' monitoring frameworks. Such integrative steps would ensure a holistic, adaptable approach to sustainability assessment, in line with the EU taxonomy, and enhance the decision-making process for sustainable infrastructure financing. This alignment could serve as a catalyst for further research and policy development, ensuring comprehensive coverage of sustainability dimensions in infrastructure projects.

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References

1. Wright, H.; Dimsdale, T.; Healy, C.; Orozco, D.; Williamson, S.; Mabey, N. *Sustainable Infrastructure and the Multilateral Development Banks: Changing the Narrative*; E3G: London, UK, 2018; Available online: http://www.jstor.org/stable/resrep21743 (accessed on 8 November 2021).
2. Himberg, H. Comparative Review of Multilateral Development Bank Safeguard Systems. 2015. Available online: https://consultations.worldbank.org/content/dam/sites/consultations/doc/migration/mdb_safeguard_comparison_main_report_and_annexes_may_2015.pdf (accessed on 16 March 2024).
3. Polk, D. *Environmental & Social Standards in Project Finance: Overview, Current State of Play*; Davis Polk: New York, NY, USA, 2017.
4. Horberry, J. Environmental and Social Safeguards. Evidence on Demand, UK, 2014; p. iv + 29. Available online: https://assets.publishing.service.gov.uk/media/57a089aae5274a27b20001dd/EoD_HDYr3_12_Dec2014_Clim_Env_Safeguards.pdf (accessed on 16 March 2024).
5. Bueno, P.C.; Vassallo, J.M.; Cheung, K. Sustainability Assessment of Transport Infrastructure Projects: A Review of Existing Tools and Methods. *Transp. Rev.* **2015**, *35*, 622–649. [CrossRef]
6. Gilmour, D.; Blackwood, D.; Banks, L.; Wilson, F. Sustainable development indicators for major infrastructure projects. *Proc. Inst. Civ. Eng.-Munic. Eng.* **2011**, *164*, 15–24. [CrossRef]
7. Tsai, C.Y.; Chang, A.S. Framework for developing construction sustainability items: The example of highway design. *J. Clean. Prod.* **2012**, *20*, 127–136. [CrossRef]
8. Ji, S.M. *A Comparative Analysis on the Environmental and Social Safeguard Policies of the Multilateral Development Banks-Based on the Sustainable Development Goals*; Escuela de Graduados de Universidad Nacional de Seúl: Seoul, Republic of Korea, 2018.
9. Narain, D.; Sonter, L.J.; Lechner, A.M.; Watson, J.E.; Simmonds, J.S.; Maron, M. Global Assessment of the Biodiversity Safeguards of Development Banks That Finance Infrastructure. *Conserv. Biol.* **2023**, *37*, e14095. [CrossRef] [PubMed]
10. OVE. Evaluación de las Salvaguardias Ambientales y Sociales. 2018. Available online: https://publications.iadb.org/es/publicacion/17295/documento-de-enfoque-evaluacion-de-salvaguardias-ambientales-y-sociales (accessed on 16 March 2024).
11. Tommaso, C.D.; Thornton, J. Do ESG Scores Effect Bank Risk Taking and Value? Evidence from European Banks. *Corp. Soc. Responsib. Environ. Manag.* **2020**, *27*, 2286–2298. [CrossRef]
12. Buallay, A.; Fadel, S.M.; Al-Ajmi, J.; Saudagaran, S.M. Sustainability Reporting and Performance of MENA Banks: Is There a Trade-Off? *Meas. Bus. Excell.* **2020**, *24*, 197–221. [CrossRef]
13. Yuan, F.; Gallagher, K.P. *Infrastructure for Sustainable Development: The Role of National Development Banks*; Boston University: Boston, MA, USA, 2016.
14. Dann, P.; Riegner, M. The World Bank's Environmental and Social Safeguards and the evolution of global order. *Leiden J. Int. Law* **2019**, *32*, 537–559. [CrossRef]
15. Chen, R. Impact of ESG Score on Firms' Performance Based on Empirical Examination of the Chinese Stock Market. *BCP Bus. Manag.* **2023**, *38*, 2948–2953. [CrossRef]
16. Cordazzo, M.; Bini, L.; Marzo, G. Does the EU Directive on Non-financial Information Influence the Value Relevance of ESG Disclosure? Italian Evidence. *Bus. Strategy Environ.* **2020**, *29*, 3470–3483. [CrossRef]
17. Kousis, I.; Laskari, M.; Ntouros, V.; Assimakopoulos, M.-N.; Romanowicz, J. An Analysis of the Determining Factors of Fuel Poverty among Students Living in the Private-Rented Sector in Europe and Its Impact on Their Well-Being. *Energy Sources Part B Econ. Plan. Policy* **2020**, *15*, 113–135. [CrossRef]
18. Ballinger, R. *On the Edge: Coastal Governance and Risk*; Springer: Dordrecht, The Netherlands, 2014. [CrossRef]
19. Lucarelli, C.; Mazzoli, C.; Rancan, M.; Severini, S. Classification of Sustainable Activities: EU Taxonomy and Scientific Literature. *Sustainability* **2020**, *12*, 6460. [CrossRef]
20. Soria-Lara, J.A.; Arce-Ruiz, R.M.; Arranz-López, A.; Ariza-Álvarez, A. Environmental Impact Assessment for transport projects: A review of technical and process-related issues. *Adv. Transp. Policy Plan.* **2020**, *6*, 255–285.
21. Pendergast, C.; Kysel, I.M. A Framing Paper: Multilateral Development Banks & Human Rights. In Proceedings of the Samuel Dash Conference on Human Rights, Washington, DC, USA, 7 April 2014.
22. Sahely, H.; Kennedy, C.; Adams, B. Developing sustainability criteria for urban infrastructure systems. *Can. J. Civ. Eng.* **2005**, *32*, 72–85. [CrossRef]
23. Humphrey, C. *Time for a New Approach to Environmental and Social Protection at Multilateral Development Banks*; Overseas Development Institute: London, UK, 2016.
24. Qin, L. Pressure Mounts on AIIB for Greater Clarity on Green Lending. China Dialogue. 2016. Available online: https://dialogue.earth/en/business/8554-pressure-mounts-on-aiib-for-greater-clarity-on-green-lending/ (accessed on 16 March 2024).

25. Nelson, P.J. Multilateral development banks, transparency and corporate clients: 'public–private partnerships' and public access to information. *Public Adm. Dev.* **2003**, *23*, 249–257. [CrossRef]
26. Schumacher, K.; Chenet, H.; Volz, U. Sustainable Finance in Japan. *J. Sustain. Financ. Investig.* **2020**, *10*, 213–246. [CrossRef]
27. Jain, K.; Tripathi, P.S. Mapping the Environmental, Social and Governance Literature: A bibliometric and Content Analysis. *J. Strategy Manag.* **2023**, *16*, 397–428. [CrossRef]
28. Piemonte, C.; Cattaneo, O.; Morris, R.; Pincet, A.; Poensgen, K. *Transition Finance*; OECD: Paris, France, 2019. [CrossRef]
29. Al Amosh, H.; Khatib, S.F.; Ananzeh, H. Terrorist attacks and environmental social and governance performance: Evidence from cross-country panel data. *Corp. Soc. Responsib. Environ. Manag.* **2024**, *31*, 210–223. [CrossRef]
30. Sala, S.; Ciuffo, B.; Nijkamp, P. A systemic framework for sustainability assessment. *Ecol. Econ.* **2015**, *119*, 314–325. [CrossRef]
31. ICE. Proceedings of the Institution of Civil Engineers 2003. *Inst. Civ. Eng.-Eng. Sustain.* **2003**, *156*, 221–222. [CrossRef]
32. Clevenger, C.M.; Ozbek, M.E.; Simpson, S. Review of sustainability rating systems used for infrastructure projects. In *49th ASC Annual International Conference Proceedings*; Associated Schools for Construction: Fort Collins, CO, USA, 2013; pp. 10–13.
33. Vassallo, J.M.; Bueno, P.C. Sustainability assessment of transport policies, plans and projects. In *Advances in Transport Policy and Planning*; Elsevier: Amsterdam, The Netherlands, 2021; Volume 7, pp. 9–50.
34. Hezri, A.A. Sustainability indicator system and policy processes in Malaysia: A framework for utilisation and learning. *J. Environ. Manag.* **2004**, *73*, 357–371. [CrossRef] [PubMed]
35. Martland, C.D. *Toward More Sustainable Infrastructure*; Wiley: Hoboken, NJ, USA, 2012.
36. Devuyst, D. Linking impact assessment and sustainable development at the local level: The introduction of sustainability assessment systems. *Sustain. Dev.* **2000**, *8*, 67–78. [CrossRef]
37. Diaz-Sarachaga, J.M.; Jato-Espino, D.; Castro-Fresno, D. Methodology for the development of a new Sustainable Infrastructure Rating System for Developing Countries (SIRSDEC). *Environ. Sci. Policy* **2017**, *69*, 65–72. [CrossRef]
38. Gibberd, J. Assessing sustainable buildings in developing countries–the sustainable building assessment tool (SBAT) and the sustainable building lifecycle (SBAT). In Proceedings of the World Sustainable Building Conference, Tokyo, Japan, 27–29 September 2005; pp. 1605–1612.
39. Griffiths, K.; Boyle, C.; Henning, T.F.P. Infrastructure sustainability rating tools—Exploring opportunities for the engineering profession based on international research. *Aust. J. Civ. Eng.* **2020**, *18*, 18–28. [CrossRef]
40. UNOPS. *Building for a Sustainable Future*; UNOPS: Copenhagen, Denmark, 2012.
41. Diaz-Sarachaga, J.M. Development and Application of a New Sustainable Infrastructure Rating System for Developing Countries (SIRSDEC). Ph.D. Thesis, University of Oviedo, Oviedo, Spain, 2017.
42. Griffiths, K.; Boyle, C.; Henning, T. Comparative assessment of infrastructure sustainability rating tools. In Proceedings of the Transportation Research Board 96th Annual Meeting, Washington, DC, USA, 8–12 January 2017.
43. Kaur, H.; Garg, P. Urban sustainability assessment tools: A review. *J. Clean. Prod.* **2019**, *210*, 146–158. [CrossRef]
44. Muench, S.T.; Armstrong, A.; Allen, B. Sustainable Roadway Design and Construction in Federal Lands Highway Program. *Transp. Res. Rec.* **2012**, *2271*, 19–30. [CrossRef]
45. Nguyen, B.K.; Altan, H. Comparative review of five sustainable rating systems. *Procedia Eng.* **2011**, *21*, 376–386. [CrossRef]
46. Jacobs, S.; Burkhard, B.; Van Daele, T.; Staes, J.; Schneiders, A. 'The Matrix Reloaded': A review of expert knowledge use for mapping ecosystem services. *Ecol. Model.* **2015**, *295*, 21–30. [CrossRef]
47. African Development Bank Group. AfDB'S Integrated Safeguards System—Policy Statement and Operational Safeguards. *African Development Bank. December 2013.* Available online: https://www.afdb.org/sites/default/files/documents/policy-documents/december_2013_-_afdbs_integrated_safeguards_system_-_policy_statement_and_operational_safeguards.pdf (accessed on 16 March 2024).
48. Foucault, M. 12 December 1973. In *Psychiatric Power*; Springer: Dordrecht, The Netherlands, 2006; pp. 123–142.
49. Burkhard, B.; Kroll, F.; Nedkov, S.; Müller, F. Mapping ecosystem service supply, demand and budgets. *Ecol. Indic.* **2012**, *21*, 17–29. [CrossRef]
50. Shandalov, Y.; Egozi, D.; Koffler, J.; Dado-Rosenfeld, D.; Ben-Shimol, D.; Freiman, A.; Shor, E.; Kabala, A.; Levenberg, S. An engineered muscle flap for reconstruction of large soft tissue defects. *Proc. Natl. Acad. Sci. USA* **2014**, *111*, 6010–6015. [CrossRef] [PubMed]
51. Grimmer, J.; Stewart, B.M. Text as data: The promise and pitfalls of automatic content analysis methods for political texts. *Political Anal.* **2013**, *21*, 267–297. [CrossRef]
52. Mische, A. Measuring futures in action: Projective grammars in the Rio+ 20 debates. *Theory Soc.* **2014**, *43*, 437–464. [CrossRef]
53. Krippendorff, K. *Content Analysis: An Introduction to Its Methodology*; Sage Publications: Thousand Oaks, CA, USA, 2018.

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Does the Water Rights Trading Policy Improve Water-Use Efficiency? An Environmental Policy Evaluation from China

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Abstract: As a crucial basic natural resource, water resources are the cornerstone for sustainable national economic development. This paper takes the 2014 pilot water rights trading policy (WRT) as an entry point and uses a difference-in-differences (DID) model to test the policy effect of WRT on water-use efficiency (WUE) based on panel data for 30 Chinese provinces from 2005 to 2021. The study shows that WRT can significantly improve the regional WUE, and these results remain valid after a series of robustness tests, such as the parallel trend test, placebo test, and PSM-DID. Mechanistic analysis revealed that WRT can produce the Porter effect, which affects the WUE through technological innovation. The results of the heterogeneity analysis based on the synthetic control method (SCM) showed that WRT effectively improved WUE in Jiangxi, Henan, Ningxia, Hubei, and Guangdong, but did not achieve the expected effect in Inner Mongolia or Gansu. This paper provides solid empirical support for assessing the effectiveness of WRT and accelerating the process of establishing a unified national WRT market in China by 2025.

Keywords: water rights trading policy; water-use efficiency; difference-in-differences; China; technological innovation; synthetic control method; environmental policy evaluation

1. Introduction

Approximately 4 billion people globally are facing severe water shortages [1]. Water scarcity and inefficient utilization have become global problems that hinder the sustainable development of national economies [2,3]. In response to the current situation, countries worldwide have also implemented several policies [4–7]. However, the public nature and scarcity of water resources often lead to a "Tragedy of the Commons". In this case, the use of water rights trading as a market mechanism has become a key measure for solving the contradiction between supply and demand [8].

Since 1980, developed countries have gradually explored the exploration of water rights markets and achieved excellent performance [9]. In 2000, China's first water rights trading incident in Zhejiang Province triggered widespread public concern [10]. In 2005, the Ministry of Water Resources (MWR) issued "Several Opinions on the Transfer of Water Rights", which clarified the principles and scope of water rights trading [11]. In 2014, the central government proposed a sixteen-word policy for water management in the new period. In the same year, the MWR issued the "Notice on the Pilot Work of Water Rights", in which seven provinces, namely, Jiangxi, Henan, Ningxia, Hubei, Guangdong, Inner Mongolia, and Gansu, were selected to carry out the pilot work of water rights trading [12]. The notice requires pilot provinces to carry out water rights reform under the premise of controlling total water consumption, forcing water resources to be used efficiently [13]. Subsequently, Shandong, Zhejiang, and other places began to explore water rights at the provincial level [14]. In 2016, the China Water Exchange was established in Beijing [15]. In 2021, the Outline of the Fourteenth Five-Year Plan explicitly proposed the development of water rights trading. In 2022, the Chinese government issued the "Guiding Opinions on

Promoting the Reform of Water Rights", proposing the initial establishment of a national unified water-use rights trading market by 2025 [16]. To date, all seven pilot provinces have been engaging in water rights trading for nearly 10 years. Therefore, has the pilot water rights trading policy (WRT) improved regional water-use efficiency (WUE)? This paper studies and analyses this topic.

Much of the current literature examining the effects of environmental equity trading policies still focuses primarily on carbon emission rights, sewage rights, energy rights, etc., while there are fewer studies on water rights trading policy. Zhang (2014) explored the positive economic effect of WRT through theoretical analysis and case verification based on analyzing the national situation of water shortages in China [17]. Ma et al. (2021) constructed a difference-in-differences (DID) model through three periods of microdata from 2007, 2012, and 2017 [18], and verified that water rights registration and trading are conducive to improving farmers' irrigation behavior to produce water-saving effects. However, these three-period cross-sectional data cannot be used for parallel trend tests. Zhu et al. (2022) explored the positive impact of WRT on regional water quality and quantity by constructing a coupled water quality and quantity model [19]. By constructing a spatial difference-in-differences (SDID) model, Du et al. (2022) concluded that there are no spatial spillovers from policies on water rights trading [20]. Heaney et al. (2006) investigated the third-party effects of WRT in Australia and its countermeasures [21]. Fang et al. (2021) concluded that WRT helps to guarantee food security in China through the use of a DID model for estimation [22]. Liu et al. (2022) found that WRT can have an impact on Chinese corporate investment through two major mechanisms, namely, optimizing the allocation of resources and reducing corporate risk [23].

Overall, due to the late introduction of WRT in China, relatively few related studies exist. Although there is also literature focusing on the policy effects of WRT, it is not sufficient in terms of sample selection, mediation path tests, and heterogeneity analysis of different pilot provinces. In contrast, this paper may be innovative in the following aspects. First, this paper selects 17 periods of long-panel data of 30 Chinese provinces from 2005 to 2021 to obtain a more complete and updated sample, which further improves the unbiasedness and validity of the estimation results. By constructing the DID model, the overall average treatment effect and the long-term dynamic effect of WRT on WUE in seven pilot provinces can be effectively identified. In addition, this paper conducts a series of robustness tests, including a parallel trend test, placebo test, PSM-DID, etc., which are more adequate than those used in previous studies. Second, this paper explores the mediating pathway of WRT's impact on WUE, i.e., technological innovation, which helps to complement the literature on the analysis of WUE impact mechanisms. Third, this paper innovatively introduces the synthetic control method (SCM) to the heterogeneity analysis of the seven pilot regions. Unlike previous studies that mostly divided the pilot provinces into eastern, central, and western regions for group regression, this paper uses SCM to simulate the virtual path of WUE change from 2005 to 2021 in the seven pilot provinces of Jiangxi, Henan, Ningxia, Hubei, Guangdong, Inner Mongolia, and Gansu to compare it with the actual path to realize heterogeneity analysis of the policy effects in each province. This provides a basis for the targeted implementation of WRT in the future in each pilot province. The results of this paper provide a reference for China to establish a national unified water rights trading market by 2025 to further realize the sustainable development of water resources.

2. Theoretical Mechanisms

To avoid the "Tragedy of the Commons", water rights reform, based on confirming and registering the right to use water resources, further imposes an excessively progressive tariff on the excess use of water and empowers water users to transfer water savings within the scope of their rights [18]. On the one hand, water rights and excess progressive tariff levies strengthen water scarcity. The water subject, as a rational decision maker, will be prompted by the increase in the cost of water use to increase its awareness of water

conservation, change its water-use mode, and improve the efficiency of water resource utilization [24,25]; on the other hand, the flow authority of the saved water further deepens the motivation of the water subject to conserve water and prompts further investment in water-saving technologies and profits through market transactions. Accordingly, the article proposes the following:

Hypothesis 1 (H1). *WRT improves WUE*.

As a market-led environmental management system [26], WRT may enhance WUE through technological innovation and industrial structure upgrading. First, WRT may be used to improve WUE through technological innovation. Under the cost–control incentive mechanism, water users increase their investment in promoting technological innovation to minimize the loss caused by purchasing water rights indicators. In addition, the government can generate revenue from the reimbursable use of water resources, which in turn can lead to the research and development of water-saving technologies. Second, WRT may also enhance the WUE through industrial structure upgrading. At present, China's agriculture accounts for more than 60% of the total water consumption, and the industrial and service sectors account for a relatively small amount [27] of the total water consumption. Problems such as large channel leakage loss and large water flood irrigation have led to low agricultural WUE and serious waste of water resources in China [28]. Through water rights trading, farmers can be prompted to improve their awareness of water conservation, adopt more efficient irrigation methods, and transfer saved water resource indicators to industries with higher WUE to improve the overall regional WUE. Accordingly, the article proposes the following:

Hypothesis 2 (H2). *WRT improves WUE through technological innovation*.

Hypothesis 3 (H3). *WRT improves WUE through industrial structure upgrading*.

Summarizing the above analysis, the theoretical mechanism of this paper is shown in Figure 1.

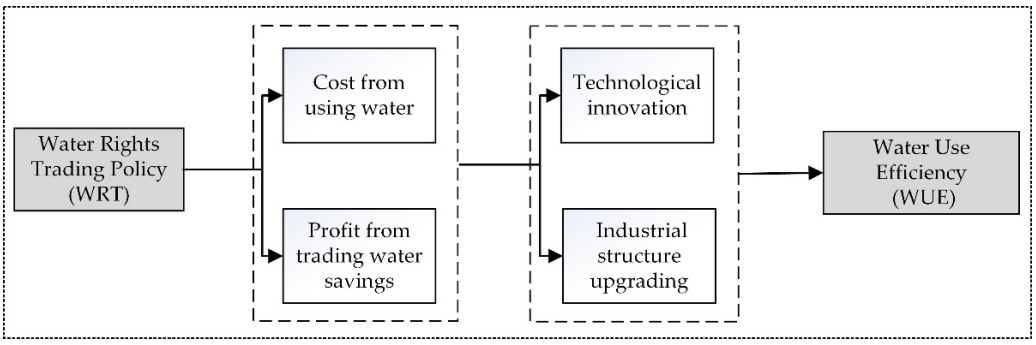


Figure 1. Theoretical mechanism of the impact of WRT on WUE.

3. Materials and Methods

3.1. Model Setting

The DID model is a commonly used model for evaluating policy effects [29]; this model divides the experimental subjects into treatment and control groups. When the two groups satisfy the parallel trend assumption, the average treatment effect of the policy can be measured. The "Notice on the Pilot Work of Water Rights" issued in 2014 constitutes a "quasi-natural experiment". On this basis, this study intends to select seven pilot provinces as the treatment group and other provinces as the control group and analyze the policy effects of WRT using the set DID model:

$$W_{it} = \beta_0 + \beta_1 treat_i \times post_t + \alpha_s X_{it} + \mu_i + v_t + \varepsilon_{it} \quad (1)$$

where i denotes the province, t denotes the year, and W is the water-use efficiency of a province. This paper adopts water consumption per unit of GDP as a metric; treat is a dummy variable for WRT; if a province has carried out a pilot of water rights trading, then treat = 1, and, vice versa, treat = 0; post is a time dummy variable; if the year is 2014 or after 2014, then post = 1, and, vice versa, post = 0; X represents the control variables affecting regional water-use efficiency, specifically including economic development level, water resource endowment, industrial structure, and trade openness; μ_i and v_t represent fixed effects at the province and time level, respectively; and ε_{it} represents the residual term. In Equation (1), the core explanatory variable is β_1. A negative β_1 indicates that WRT can enhance the regional WUE.

3.2. Sample and Data

Given the problems of data availability and missing data, this article excludes the sample cases of Hong Kong, Macao, Taiwan, and Tibet and finally selects panel data for 30 Chinese provinces from 2005 to 2021 for analysis. All of the data were obtained from the *China Statistical Yearbook*. And all of the variables were logarithmized in this paper to avoid excessive data fluctuations. Moreover, all of the price-related data in this paper were deflated with 2005 as the base period.

3.3. Variable Selection

3.3.1. Dependent Variable

The dependent variable is water-use efficiency. In this paper, the water consumption per unit of GDP is chosen for measurement. This indicator can be calculated by dividing the total regional water supply by the regional GDP; it reflects the water consumed per unit of GDP produced during the economic activities of a certain region, and it is an important indicator reflecting the regional WUE.

3.3.2. Independent Variable

The independent variable is the water rights trading policy. This paper assigns values to the variables for each province based on the "Notice on the Pilot Work of Water Rights" issued by the MWR. If a province has carried out a pilot WRT in the current year, the value is 1; otherwise, the value is 0.

3.3.3. Control Variables

Based on the literature [19,30], this paper chooses the economic development level, water resource endowment, industrial structure, and trade openness as control variables.

3.3.4. Channel Variables

This paper selects technological innovation and industrial structure upgrading as channel variables. Technological innovation is measured by R&D expenditure per capita for industrial enterprises above a designated size. Industrial structure upgrading builds upon Yu et al. (2021) [31] and is characterized by assigning values to three subindustries and weighting them to obtain the industrial structure hierarchy coefficient. The calculation formula is as follows.

$$str = \sum_{i=1}^{3} (y_i \times i) \quad (2)$$

where y_i represents the proportion of value added of industry i in GDP. The descriptive statistics of the variables are shown in Table 1.

Table 1. Descriptive statistics.

Variable Type	Variables	Symbol	Mean	SD	Min	Max	Median
Dependent variable	Water-use efficiency (water consumption per unit of GDP)	WUE	206.1999	233.6903	16.0326	1952.6225	135.6421
Independent variable	Water rights trading policy (1 if a province pilots a water rights trading policy, 0 otherwise)	WRT	0.2333	0.4234	0.0000	1.0000	0.0000
Control variables	Economic development level (real GDP per capita)	economic	3.6607	2.3115	0.5306	13.4626	3.1201
	Water resource endowment (water supply per capita)	water	506.3816	418.2610	161.2000	2657.4000	436.1500
	Industrial structure (share of value added of the secondary industry in GDP)	industrial	44.5576	8.7548	15.8337	61.4777	45.9142
	Trade openness (total exports and imports/GDP)	openness	0.2874	0.3237	0.0071	1.7085	0.1486
Channel variables	Technological innovation (R&D expenditure per capita for industrial enterprises above designated size)	technology	642.9264	630.5500	10.2670	3194.0084	398.4043
	Industrial structure upgrading (industrial structure hierarchy coefficient)	upgrade	2.3426	0.1346	2.0722	2.8357	2.3205

4. Results and Discussion

4.1. Benchmark Regression Results

This article uses the DID model to test hypothesis 1, and Table 2 shows the regression results. Column (1) in the table does not incorporate control variables but simply controls for time-fixed effects and province-fixed effects; column (2) further incorporates control variables on top of column (1) as a way of avoiding possible bias in the results. The regression coefficients of WRT are significantly negative regardless of the inclusion of control variables, indicating that WRT can effectively improve WUE. By analyzing the regression results with the inclusion of control variables, it can be found that the regression coefficient of the WRT is −0.0077, which indicates that the water consumption per unit of GDP in the pilot provinces decreases by 0.77% compared with that in the nonpilot provinces. The statistical results in Table 2 verify hypothesis 1; that is, WRT can improve WUE.

Table 2. Benchmark regression results.

Variable	WUE	
	(1)	(2)
WRT	−0.0224 **	−0.0077 ***
	(−2.49)	(−3.75)
economic		−0.8570 ***
		(−9.47)
water		0.8500 ***
		(24.74)
industrial		−0.2340 ***
		(−6.54)
openness		−0.4188 ***
		(−11.30)
_cons	5.7090 ***	2.3552 ***
	(3.23×10^{14})	(8.63)
Year FE	Yes	Yes
Province FE	Yes	Yes
N	510	510
Adjusted R^2	0.9709	0.9932

Note: Values in parentheses are *t*-test values; ***, and ** indicate significance at the 1%, and 5% levels, respectively.

According to the regression results for the control variables, the coefficient of the economic development level is significantly negative at the 1% significance level, which indicates that the economic development level can effectively improve the regional WUE. A possible reason is that economic development provides the necessary conditions and motivation, such as capital and technology, for the protection of water conservation; the coefficient of water resource endowment is significantly positive at the 1% significance level, which indicates that the better the regional water resource endowment is, the lower the WUE. This may be because, in areas with better water endowments, people are less aware of water conservation, and there is wastage of water; the industrial structure coefficient at the 1% significance level is significantly negative, indicating that an increase in the proportion of value added by secondary industry can effectively improve the WUE. This phenomenon may be because, compared with agriculture, which accounts for the vast majority of China's total water consumption, the industry consumes less water and is more efficient in terms of water use. The trade openness coefficient at the 1% significance level is significantly negative, indicating that increased openness to the outside world can help further increase regional WUE. This may be because international trade agglomerations generate technological spillovers, which positively affect WUE.

4.2. Robustness Tests

4.2.1. Parallel Trend Test

Before the DID model is applied, a parallel trend test is required [32]. In this paper, the dynamic effects model is used to test for parallel trends. The approach is to take the policy implementation in 2014 as the midpoint so that the policy window is moved forward and backward by one, two, three, and four years and analyze the effect of the policy by observing the changes in the coefficients of the independent variables. The dynamic effects are modeled as follows.

$$W_{it} = \beta_0 + \sum_{n=-4}^{4} \beta_n treat_i \times post_t + \alpha_s X_{it} + \mu_i + v_t + \varepsilon_{it} \quad (3)$$

where n is the distance between the policy release time and 2014. To study the dynamic effects in the year of policy release and the 4 years before and after the policy release, n is used as an independent variable, and the rest of the variables are consistent with the meaning of Equation (1). According to the analysis in Figure 2, the regression coefficient fluctuates around the 0-axis in the first 4 years of the policy, indicating that there is no significant difference between the WUE of the two groups; the regression coefficients decreased significantly in 2014, indicating that the WUE in the pilot provinces improved significantly after policy implementation compared to that in the nonpilot provinces. However, the effect disappears after 1 year of policy implementation, which indicates that the effect is not stable enough and is recurrent. After 3 years of policy implementation, the effect becomes significant again and continues to improve in the fourth year, which indicates that there is a time lag in the improvement of WUE. At the overall level, there was a parallel trend between the two groups before 2014, and after the implementation of the policy, the pilot provinces significantly improved their WUE, which satisfied the parallel trend hypothesis.

4.2.2. Placebo Test

Drawing on the approach of Chetty et al. (2009) [33], we exclude the interference of omitted variables by randomly selecting pilot provinces for a placebo test of the model [34]. Specifically, this paper constructs dummy variables for "pseudo-WRT" by randomly generating a list of pilot provinces among all provinces. This process is repeated 500 times to obtain 500 values of β_1 based on Equation (1); then, the kernel density distribution of β_1 is plotted, as shown in Figure 3. The estimated coefficients generated based on random samples are distributed approximately 0 and follow a normal distribution. The estimated

coefficients obtained from the benchmark regression results of this article are far from 0, proving that the placebo test is passed.

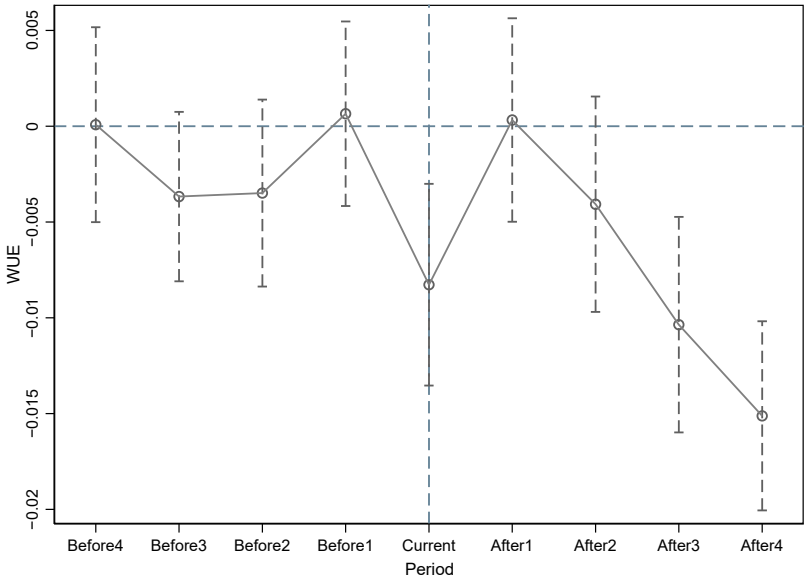


Figure 2. Parallel trend test results. Note: The circles in the figure represent the estimated coefficients of the dynamic effects of the pilot WRT, and the dashed lines are the upper and lower 90% confidence intervals.

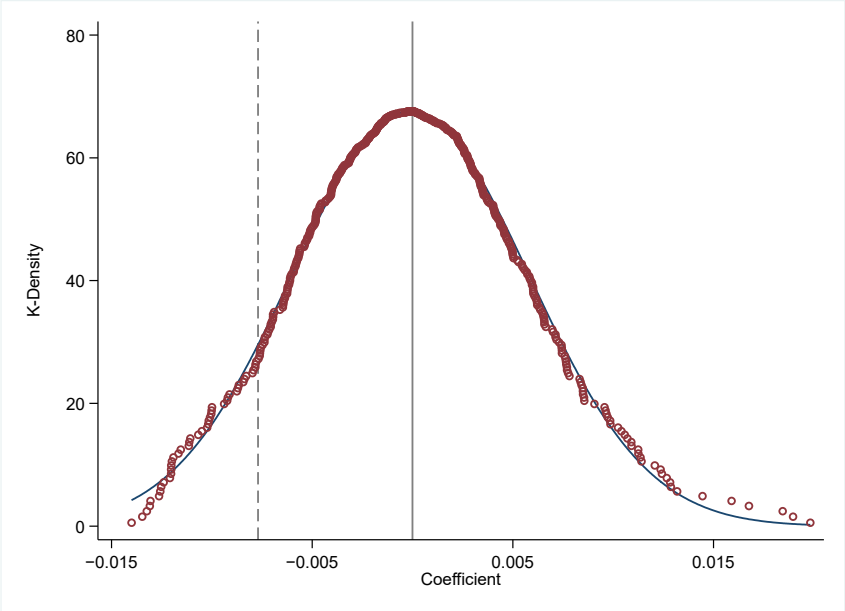


Figure 3. Placebo test results. Note: The dashed part represents the estimated coefficient (−0.0077) obtained from the results of the benchmark regression in this paper.

4.2.3. PSM-DID Model

To avoid the endogeneity problem caused by sample selection bias [35], this paper re-estimates the policy effects after matching the data with propensity scores using the caliper matching method. Before propensity score matching, a balancing test was needed. The results of the balance test reveal that the absolute value of the standardized deviation of each matched variable is less than 10%. Moreover, the t-test results for all control variables after matching do not support the original hypothesis; that is, there is no significant difference between the two groups after matching. This indicates that the matching method

in this paper is appropriate and achieves a better matching effect. Column (1) of Table 3 shows the estimation results for PSM-DID. The results show that the estimated coefficients of WRT are significantly negative at the 10% level, which further validates the conclusion that WRT can effectively improve the regional WUE.

Table 3. Robustness test results.

Variable	WUE					
	(1)	(2)	(3)	(4)	(5)	(6)
WRT	−0.0040 *	−0.0073 ***	−0.0122 ***	−0.0118 ***	−0.0453 *	−0.0099 **
	(−2.04)	(−3.79)	(−3.28)	(−3.44)	(−1.80)	(−2.36)
pre-WRT		−0.0004				
		(−0.31)				
_cons	2.3396 ***	2.3552 ***	2.7433 ***	2.7416 ***	2.8146 **	2.6828 ***
	(9.66)	(8.63)	(11.54)	(10.42)	(2.40)	(9.56)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Baseline variable × time trend	No	No	No	No	No	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes	Yes	Yes
N	480	510	340	320	510	510
Adjusted R^2	0.9935	0.9932	0.9935	0.9940	0.8778	0.9940

Note: Values in parentheses are *t*-test values; ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

4.2.4. Other Robustness Tests

(1) Expected effects test

Examining the expected effects of policy implementation is critical for analyzing the robustness of the regression results. Before the start of the WRT pilot, provinces may have made preparations for the policy in advance. To address this situation, this paper adds the WRT variable of the preceding period to the baseline regression. As shown in column (2) of Table 3, the estimated coefficients and significance of WRT are generally consistent with the original regression results, while the regression coefficients of pre-WRT are not significant. The above results prove that the expectation for WRT does not influence the estimation results in this paper.

(2) Controlling for other policy impacts

The introduction of other major national water resources management policies is also likely to improve WUE, which may lead to a bias in our estimate of the effect of the WRT. In 2016, Hebei Province took the lead in launching a pilot water resources tax collection. In 2017, the state further extended its pilot scope to include the following nine provinces: Beijing, Tianjin, Shanxi, Inner Mongolia, Shandong, Henan, Sichuan, Shaanxi, and Ningxia, ultimately forming a new pattern of "1 + 9" pilots [36]. To avoid the possibility that the dummy variables we set for the WRT may contain shocks from the water resources tax policy, we need to further exclude the interference of this policy to conduct robustness tests. Based on this, this paper rearranges the regression after excluding the sample that carries out the water resources tax pilot, and the regression results are shown in column (3) of Table 3. After excluding the impact of the water resources tax policy, the WRT is still effective at enhancing the WUE of the pilot area at the 1% significance level, which indicates that the baseline regression results in this paper are robust.

(3) Excluding the impact of provincial water rights pilots

After the implementation of the central WRT, the 10 provinces of Shandong, Zhejiang, Xinjiang, Fujian, Liaoning, Hebei, Hunan, Shaanxi, Shanxi, and Jilin established their own provincial water rights reform policy pilots that are in line with the development characteristics of their regions. Failure to consider the impact of provincial water rights pilots may lead to an underestimation of the effect of the central water rights trading policy.

Accordingly, this paper excludes provinces with provincial water rights pilots from the control group for regression, and column (4) of Table 3 shows the results. After excluding the effect of the provincial water rights pilots, WRT still significantly improved WUE at the 1% significance level. Moreover, the regression coefficient changes from -0.0077 to -0.0118, which further strengthens the impact effect and indicates that the effect of the national provincial water rights pilots is greater than that of the provincial water rights pilots.

(4) Replacing the dependent variable

The water consumption of 10 thousand RMB of industrial added value is regressed as a dependent variable to measure WUE and column (5) of Table 3 shows the results. After the dependent variable was replaced, the WRT still significantly improved the WUE, indicating that the benchmark regression results were robust.

(5) Inclusion of benchmark variables to mitigate selection effects

When applying the DID model, the list of provinces for the WRT pilot would ideally be randomly selected. If the selection of pilot provinces is correlated with benchmark variables such as regional water resources, population, and economic development, this may lead to estimation bias over time. To avoid the effect of nonrandom selection, this paper includes total water supply, year-end population, and GDP as proxy variables for the baseline variable in the regression of Equation (1), and the results are shown in column (6) of Table 3. After adding the interaction term between the benchmark variable and the linear trend in time, WRT passes the test at the 5% significance level, indicating that the policy can significantly improve WUE, which is consistent with the results of the benchmark regression.

5. Mechanism and Heterogeneity Analysis

5.1. Mechanism Analysis

In this section, the path of the impact of WRT on WUE is further investigated through a mechanism test. The causal step method proposed by Baron et al. (1986) is utilized to test the specific mechanism of enhancement from two perspectives [37]: technological innovation and industrial structure upgrading. The model is set as follows:

$$M_{it} = \beta_0 + \beta_2 treat_i \times post_t + \alpha_s X_{it} + \mu_i + v_t + \varepsilon_{it} \quad (4)$$

$$W_{it} = \beta_0 + \beta_3 treat_i \times post_t + \beta_4 M_{it} + \alpha_s X_{it} + \mu_i + v_t + \varepsilon_{it} \quad (5)$$

where M_{it} represents the channel variables in this paper, which are the R&D expenditure per capita for industrial enterprises above the designated size and the industrial structure hierarchy coefficient. If β_2 in Equation (3) and β_3 and β_4 in Equation (4) are significant, then WRT can improve WUE through this channel variable. Conversely, the variable is not a channel variable.

In Table 4, columns (1) and (2) test whether WRT can achieve WUE enhancement through technological innovation. Column (1) shows that WRT significantly improves technological innovation; that is, WRT can generate the Porter effect to promote technological innovation and development. In column (2), both the WRT coefficients and the technological innovation coefficients are significantly negative, indicating that WRT can enhance WUE through technological innovation. Thus, hypothesis 2 can be tested. Columns (3) and (4) of Table 4 test whether industrial structure upgrading is a suitable channel variable. Column (3) shows that WRT positively contributes to regional industrial structure upgrading at the 1% significance level. However, in column (4), the regression coefficient of industrial structure upgrading is not significant, which indicates that it is not a suitable mechanism variable; thus, hypothesis 3 is rejected. In summary, the enhancement effect of WRT on WUE is realized mainly through technological innovation.

Table 4. Mechanism test results.

Variable	Technology	WUE	Upgrade	WUE
	(1)	(2)	(3)	(4)
WRT	0.1356 *	−0.0059 **	0.0042 ***	−0.0070 **
	(1.82)	(−2.61)	(4.91)	(−2.83)
Technology		−0.0133 *		
		(−2.08)		
upgrade				−0.1558
				(−1.12)
_cons	−5.1310	2.2870 ***	1.1838 ***	2.5396 ***
	(−1.52)	(8.49)	(17.66)	(8.44)
Control variables	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes
N	510	510	510	510
Adjusted R^2	0.7851	0.9934	0.8802	0.9932
Intermediary effect	−0.0018		-	
Direct effect	−0.0059		-	
Total effect	−0.0077		-	
Intermediation effect as a percentage	23.38%		-	

Note: Values in parentheses are *t*-test values; ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

After the directional analysis of the impact path, this paper draws on Hicks et al. (2011) to further quantify the direct and indirect effects of WRT on WUE [38], and Table 4 shows the results. The direct effect is −0.0059, and the mediated effect is −0.0018. Among them, the mediated effect accounts for 23.38% of the total effect. This indicates that 23.38% of WRT's effect on WUE is realized through technological innovation.

5.2. Heterogeneity Analysis

Drawing on Ji et al. (2021) [39], the SCM is used to study the policy effects in different provinces. To maintain consistency with the previous paper, this paper takes 2005–2021 as the policy study interval, chooses all the control variables as predictor variables, takes 23 nonpilot provinces as the control group, and synthesizes the water consumption per unit of GDP of seven pilot provinces according to different weights. Trends in the logarithm of water consumption per unit of GDP in the pilot and synthetic pilot provinces are shown in Figure 4, with the dashed line representing the year 2014, when WRT was initiated.

Figure 4 shows that WRT effectively reduces water consumption per unit of GDP in Jiangxi, Henan, Ningxia, and Hubei, i.e., it improves WUE; however, in Guangdong, the effect is not as obvious, although consumption has decreased. A possible reason is that Guangdong Province has a developed economy, a stable water-use structure, and advanced water-saving technologies, so the room for improvement and effect of the WRT are not obvious. In addition, the region has relatively abundant water resources, and water consumption has not yet reached the "ceiling" level. Therefore, the demand and enthusiasm for WRT are insufficient, and the market is limited; it is worth noting that after the pilot of WRT, the expected results were not achieved in Inner Mongolia and Gansu. First, related to the structure of water use in the province, Inner Mongolia and Gansu have absolute proportions of water used for agriculture, while industry and services are less developed and consume less water. Water rights transactions are mainly concentrated among agricultural irrigation water users, and the number of water rights transactions transferred to industry and services is relatively small; thus, temporary borrowing of water rights between farmers has no significant impact on WUE. Second, the original water diversion program is no longer adaptable to the current water-use situation in Inner Mongolia and Gansu, and the water resource monitoring and measurement system has not

yet improved, resulting in a large amount of water resources being overutilized. Under strict control of total water resources, the continued implementation of the original water-sharing program will lead to the coexistence of WRT and water resource overuse, which will lead to a situation that contradicts the expected effect of WRT.

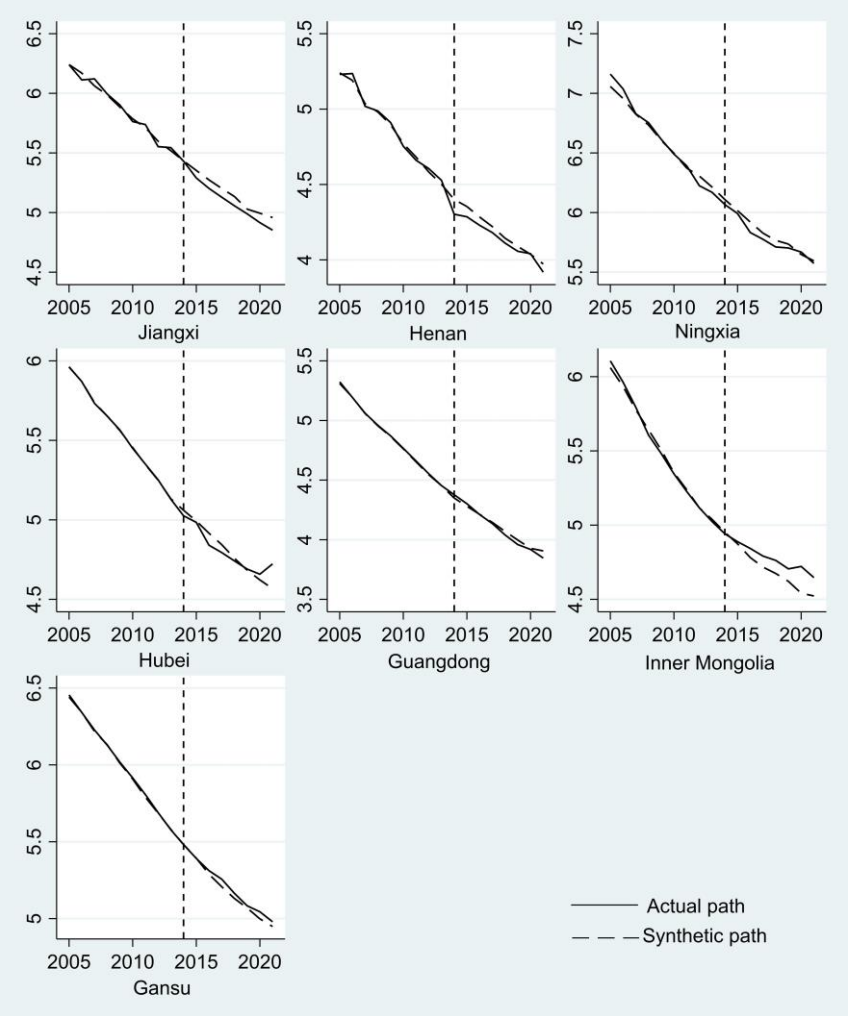


Figure 4. Heterogeneity analysis. Note: The *x*-axis represents years, and the *y*-axis represents the logarithm of water consumption per unit of GDP.

Overall, WRT effectively improved the WUE in most of the pilot provinces and achieved better policy effects. However, as shown in Figure 4, the effect declined in all provinces until 2020, and the sustainability of WRT needed to be strengthened.

6. Conclusions and Outlook

6.1. Conclusions and Recommendations

Taking the 2014 WRT policy pilot as an entry point, this paper constructs a DID model to assess the impact of WRT on WUE based on 17 periods of panel data from 30 provinces across China from 2005 to 2021. (1) WRT can significantly improve WUE and reduce water consumption per unit of GDP by 0.77%. This conclusion still holds after the parallel trend test, placebo test, PSM-DID, and a series of other robustness tests. (2) The results of the mechanism analysis show that WRT can produce the Porter effect, which promotes the regional WUE mainly through technological innovation. (3) The results of the heterogeneity test based on the SCM showed that WRT effectively improved the WUE in Jiangxi, Henan, Ningxia, Hubei, and Guangdong but did not achieve the expected effect in Inner Mongolia or Gansu.

Based on the aforementioned findings, this paper derives several policy recommendations. (1) The WRT system should be further improved, and the construction of a unified national WRT market should be accelerated. The construction of water rights storage and transfer centers, water ecological banks, and other operating platforms should be coordinated, and innovative water rights trading financial products and trading models, such as water options and water futures, should be developed to further guide different water subjects to fulfill various forms of WRT. (2) Increase the intensity of capital investment in water-saving technologies, improve the reuse rate of water resources in industrial enterprises, reduce wastewater discharge; change crude irrigation methods in agriculture, and focus on the research and development of new water-saving irrigation equipment. (3) Improve the water resources monitoring and measurement system. Water resource monitoring and measurement are the basis for water rights trading. China should gradually establish central, basin, and local water resources monitoring and management platforms; improve water rights regulatory mechanisms; and eliminate the phenomenon of overuse of water resources. (4) Water rights trading should follow the principle of local adaptation. The government should rationally design trading modes and paths in response to the natural and social conditions of different regions to realize the efficient use of water resources and sustainable development.

6.2. Research Outlook

6.2.1. Synergies between Water Rights Trading Policy and Water Resources Tax Policy

As a public natural resource, water resources are prone to overconsumption and inefficiency in the process of development and utilization. There are three models for improving WUE: government-led, market-led, and public-led. In China, the current stage is government-led. Under the government-led model, there are usually two means to improve WUE: one is the property rights approach mentioned in this paper, i.e., intensive use of water resources through water-use rights, and the other is the Pigouvian tax, i.e., levying water resources tax. In China, WRT is still in the initial exploration stage. In the future, the questions of how to arrange the implementation direction of WRT and how to realize the coordination between WRT and water resources tax policy need to be further studied.

6.2.2. Exploring International Water Rights Trading

This paper examines the implementation of WRT in China, and the research horizon is not extended to other regions in Asia/the world, which may lead to some limitations of this paper. Currently, China's WRT is still in the early stages, and the pilot policy may have had some positive spillover effects on neighboring provinces and municipalities. It is expected that, after China builds a unified national WRT market by 2025, exploring WRT with neighboring countries to establish a broader international WRT market may become the next development trend. This may become an effective way to solve transnational river disputes, thus realizing the sustainable development and utilization of transnational river basins and the coordinated development of neighboring countries' economies by market means. The prosperity of international WRT cannot be separated from the coordination of countries, which need to clarify the relationship between national sovereignty and water rights, establish "basin-wide thinking" and focus on long-term interests. How to explore international WRT and establish a broader Asia/World unified WRT market requires further research.

It is worth noting that although WRT is currently effective in improving regional WUE in China with good policy outcomes, this does not mean that it is equally applicable to other countries. To fully utilize the advantages of WRT, there must be prerequisites such as water demand exceeds supply, good institutional arrangements, social and cultural acceptance, and sustained sources of funding. Whether WRT applies to other countries and its consequences need to be analyzed on a country-by-country basis. However, regardless

of the applicability of WRT, it is the responsibility of each country to explore nationally appropriate ways to enhance WUE for the sustainable development of water resources.

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References

1. Mekonnen, M.M.; Hoekstra, A.Y. Four billion people facing severe water scarcity. *Sci. Adv.* **2016**, *2*, 6. [CrossRef]
2. Vörösmarty, C.J.; Hoekstra, A.Y.; Bunn, S.E.; Conway, D.; Gupta, J. What scale for water governance? *Science* **2015**, *349*, 478–479. [CrossRef] [PubMed]
3. Zhou, X.Y.; Yang, Y.H.; Sheng, Z.P.; Zhang, Y.Q. Reconstructed natural runoff helps to quantify the relationship between upstream water use and downstream water scarcity in China's river basins. *Hydrol. Earth Syst. Sci.* **2019**, *23*, 2491–2505. [CrossRef]
4. Kampas, A.; Petsakos, A.; Rozakis, S. Price induced irrigation water saving: Unraveling conflicts and synergies between European agricultural and water policies for a Greek Water District. *Agric. Syst.* **2012**, *113*, 28–38. [CrossRef]
5. Wheeler, S.; Loch, A.; Zuo, A.; Bjornlund, H. Reviewing the adoption and impact of water markets in the Murray-Darling Basin, Australia. *J. Hydrol.* **2014**, *518*, 28–41. [CrossRef]
6. Zanjanian, H.; Abdolabadi, H.; Niksokhan, M.H.; Sarang, A. Influential third party on the water right conflict: A Game Theory approach to achieve the desired equilibrium (case study: Ilam dam, Iran). *J. Environ. Manag.* **2018**, *214*, 283–294. [CrossRef] [PubMed]
7. Karunananthan, M. Can the human right to water disrupt neoliberal water policies in the era of corporate policy-making? *Geoforum* **2019**, *98*, 244–253. [CrossRef]
8. Sun, Y.Y.; Jia, S.F. Basis for granting water rights and classification of water rights. *Res. Sci.* **2016**, *38*, 1893–1900.
9. Hanemann, M.; Young, M. Water rights reform and water marketing: Australia vs. the US West. *Oxf. Rev. Econ. Policy* **2020**, *36*, 108–131. [CrossRef]
10. Chen, X.N.; Wu, F.P.; Li, F.; Zhao, Y. Tradable water in Inner Mongolia's river-loop irrigation district under a high-quality development model. *China Pop. Res. Environ.* **2021**, *31*, 130–139.
11. Zhang, J.B.; Li, M.Y.; Zhu, X.M. "Quality for Quantity": A New Dimension of Water Rights Trading Reform-Logical Origins, Explanation of Elements, Practical Conditions and Institutional Safeguards. *West. Forum* **2019**, *29*, 93–100.
12. Wei, J. Exploration of water rights trading in China. *Prop. Rights Guid.* **2014**, *12*, 56–58.
13. Zhang, H.Q.; Zhou, Q.; Zhang, C.J. Evaluation of agricultural water-saving effects in the context of water rights trading: An empirical study from China's water rights pilots. *J. Clean. Prod.* **2021**, *313*, 8. [CrossRef]
14. Liu, S.Q.; Guo, S.J.; Lin, R.; Ju, D. Characteristics of China's water rights system and exploration of water rights reforms. *J. Eng. Guid.* **2016**, *8*, 12–22.
15. Liu, Y.M. The development of water rights trading in China and its pilot promotion effect. *J. Econ. Water Resour.* **2023**, *41*, 43–50+124.
16. Hao, C.X.; Dong, Z.F.; Cheng, C.Y.; Long, F.; Li, X.L.; Ge, C.Z. National Environmental Economic Policy Progress Assessment Report 2022. *Chinese J. Environ. Manag.* **2023**, *15*, 58–65.
17. Zhang, J.B. Positive Economic Effects of Water Rights Trading: Theoretical Analysis and Practical Verification. *Rur. Econ.* **2014**, *3*, 107–111.
18. Ma, J.J.; Cui, Y.; Kong, X.Z.; Chen, Z.G. Water Rights System, Water Abstraction Permit Management and Adoption of Water Saving Technologies by Farmers-An Empirical Study of the Water Saving Effect of Water Rights Reform Based on Differential Modeling. *Stat. Res.* **2021**, *38*, 116–130.
19. Zhu, J.; Chen, Y.P.; Liu, C. Impact of water rights trading policies on regional water quality and quantity. *China Pop. Res. Environ.* **2022**, *32*, 145–153.

20. Du, M.; Huang, C.; Chen, Z. Evaluating the water-saving and wastewater-reducing effects of water rights trading pilots: Evidence from a quasi-natural experiment. *J. Environ. Manag.* **2022**, *319*, 115706. [CrossRef]
21. Heaney, A.; Dwyer, G.; Beare, S.; Peterson, D.; Pechey, L. Third-party effects of water trading and potential policy responses. *Aust. J. Agr. Resour. Econ.* **2006**, *50*, 277–293. [CrossRef]
22. Fang, L.; Fu, Y.; Chen, S.J.; Mao, H. Can water rights trading pilot policy ensure food security in China? Based on the difference-in-differences method. *Water Policy* **2021**, *23*, 1415–1434. [CrossRef]
23. Liu, D.; Yu, N.Z.; Wan, H. Does water rights trading affect corporate investment? The role of resource allocation and risk mitigation channels. *Econ. Model.* **2022**, *117*, 16. [CrossRef]
24. Blakeslee, D.; Fishman, R.; Srinivasan, V. Way Down in the Hole: Adaptation to Long-Term Water Loss in Rural India. *Am. Econ. Rev.* **2020**, *110*, 200–224. [CrossRef]
25. Pashigian, B.P. A theory of prevention and legal defense with an application to the legal costs of companies. *J. Law Econ.* **1982**, *25*, 247–270. [CrossRef]
26. Svensson, J.; Wang, Y.H.; Garrick, D.; Dai, X.P. How does hybrid environmental governance work? Examining water rights trading in China (2000–2019). *J. Environ. Manag.* **2021**, *288*, 11. [CrossRef]
27. Fang, L.; Zhang, L. Does the trading of water rights encourage technology improvement and agricultural water conservation? *Agric. Water Manag.* **2020**, *233*, 8. [CrossRef]
28. Zhang, B.P. Analysis of large water flood irrigation and drip irrigation conversion adjustment in Jingdian Irrigation District. *Agric. Sci. Tech. Info.* **2022**, *14*, 26–28.
29. Perraillon, M.C.; Lindrooth, R.; Welton, J.M. Difference-in-Difference Research Designs. *Nurs. Econ.* **2019**, *37*, 328–331.
30. Tian, G.L.; Sheng, Y.; Lu, X. Study on the Impact of Water Rights Trading Market Operation on Water Resource Utilization Efficiency in Pilot Areas. *China Pop. Res. Environ.* **2020**, *30*, 146–155.
31. Yu, X.; Wang, P. Economic effects analysis of environmental regulation policy in the process of industrial structure upgrading: Evidence from Chinese provincial panel data. *Sci. Total Environ.* **2021**, *753*, 10. [CrossRef] [PubMed]
32. Ryan, A.M.; Kontopantelis, E.; Linden, A.; Burgess, J.F. Now trending: Coping with non-parallel trends in difference-in-differences analysis. *Stat. Methods Med. Res.* **2019**, *28*, 3697–3711. [CrossRef]
33. Chetty, R.; Looney, A.; Kroft, K. Salience and Taxation: Theory and Evidence. *Am. Econ. Rev.* **2009**, *99*, 1145–1177. [CrossRef]
34. Tian, J.J.; Liu, Y.J. Effectiveness of location selection of China's FDI for financial well-being: Role of digitalization. *Transform. Bus. Econ.* **2023**, *22*, 250–273.
35. Eckert, C.; Hohberger, J. Addressing Endogeneity Without Instrumental Variables: An Evaluation of the Gaussian Copula Approach for Management Research. *J. Manag.* **2023**, *49*, 1460–1495. [CrossRef]
36. Zhao, A.F.; Zhang, Y.X. An Analysis of the Impact of Water Resources Tax on Water Consumption and Water Use Efficiency—A Natural Experiment Based on the Expansion of Water Resources Tax Pilot Scheme. *Tax. Res.* **2021**, *2*, 35–41.
37. Baron, R.M.; Kenny, D.A. The moderator-mediator variable distinction in social psychological research: Conceptual, strategic, and statistical considerations. *J. Pers. Soc. Psy.* **1986**, *51*, 1173–1182. [CrossRef] [PubMed]
38. Hicks, R.; Tingley, D. Causal mediation analysis. *Stata J.* **2011**, *11*, 605–619. [CrossRef]
39. Ji, X.L.; Yang, Z. Analysis of Carbon Trading Emission Reduction Effect and Regional Differences Based on PSM-DID and SCM. *Statut. Declar.* **2021**, *37*, 154–158.

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Decision Change: The First Step to System Change

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Abstract: Global crises, such as climate change and ecological collapse, require changes in systemic factors that cause the crises. These factors include the economy, population growth, and decision-making in global affairs. Current decision-making processes have failed to accomplish the required system change, necessitating a change to these processes ('decision change') for meaningful progress. The key question is how a procedure for deciding on the required system change should be designed in this setting. In this essay, we propose a three-step approach. First, independent experts in collective decision-making should design this procedure under monitoring by auxiliary bodies that safeguard the design process; second, proposals for system change should be collected; third, based on these proposals, system change should be designed and decided upon using the new decision-making procedure. We argue that authority can be given to the new decision-making body that decides on system change. A global team must convene the decision-making experts and auxiliary bodies, collect system-change proposals, and guarantee that the decision-making process is facilitated. We call on individuals and independent organisations to form such a team or support its formation.

Keywords: climate change; decision-making; ecological collapse; meta-coordination; transformational change

1. Introduction

'Whose job is it to save the planet?' questioned journalist Fiona Harvey at the 27th Conference of the Parties (COP27) of the United Nations Framework Convention on Climate Change (UNFCCC). A sobering answer came from Wael Aboulmagd, Egypt's special representative for COP27: 'It's just futile to think that governments alone will take this challenge on' [1]. Aboulmagd is not alone in voicing this sentiment: The inability of COP27 to stimulate meaningful action strengthened calls for a different conference format, not only during the conferences [2], but also in newspapers [3–6], on websites [7–10], in politics [11], and in academia [12,13], where the calls resounded well before [14–17]. These calls have not been effective because COP28 in 2023 had the same format as COP27 in 2022. Accordingly, proposals for alternatives to the COPs have become more prominent [18–20].

Rather than closely examining such proposals, we identify an underlying 'meta-coordination' problem: there is no structure that allows us to effectively decide on alternatives to the COPs and similar conferences. The question is how and by whom an alternative decision-making procedure should be designed and what the scope of its use should be. In this essay we suggest that independent experts in collective decision-making, monitored by auxiliary bodies, design a new procedure to decide on the required system change; this design we call decision change. Additionally, we propose that a global team convenes the expert meetings, assembles the auxiliary bodies, collects system-change proposals, and initiates the decision-making on system change. These proposals constitute an actionable research programme that would have to be facilitated by an independent organisation.

This essay resulted from an integrative literature review; it is divided into nine sections. In Section 2, we work back from the COPs on biophysical crises to the underlying

problem treated in this essay—the lack of an effective 'meta-decision structure' for deciding on system change. We conclude this section by elaborating on the research question and identifying it as a case of Buchanan's meta-coordination problem. In Section 3 ('Meta-decision structures') we overview the (not entirely successful) attempts to design alternative procedures for deciding on global issues, that is, to answer the research question. Section 4 contains our main thesis: a more effective 'meta-decision structure' would consist of decision-making experts. We also describe their areas of expertise. In Section 5 we propose the design process—the programme for decision change and system change. Sections 4 and 5 thus answer the research question. The coordination of this programme by a global team is outlined in Section 6. One may counter that this programme is too convoluted or heterodox to 'save the planet'. These objections are discussed in Section 7, along with potential advantages and limitations. In Section 8 we draw conclusions and we call to action. Appendix A contains some concrete ideas as a starting point for further development.

2. Problems

In this section, we work back from the COPs on biophysical crises to the underlying problem—the lack of a structure for effectively selecting alternatives to the COPs, in particular for deciding on system change.

2.1. COPs and Crises

The main goal of COP27 was to secure the Paris Agreement [21]. This aims to limit the rising mean temperature of Earth's surface atmosphere to 2 °C, and preferably 1.5 °C (relative to the pre-industrial era), with efforts expected to increase over time [22]. COP27 resulted in some important agreements [23] which, along with other milestones [22,24–26] indicate cooperation and progress.

However, by 2022, it was almost certain that the COPs had failed to keep the temperature goal of 1.5 or 2 °C within reach, as can be deduced from Figure 1 by the Scenario Model Intercomparison Project and related findings by the Intergovernmental Panel on Climate Change (IPCC), the World Meteorological Organization, the United Nations Environment Programme, and others (details in Appendices B.1–B.4).

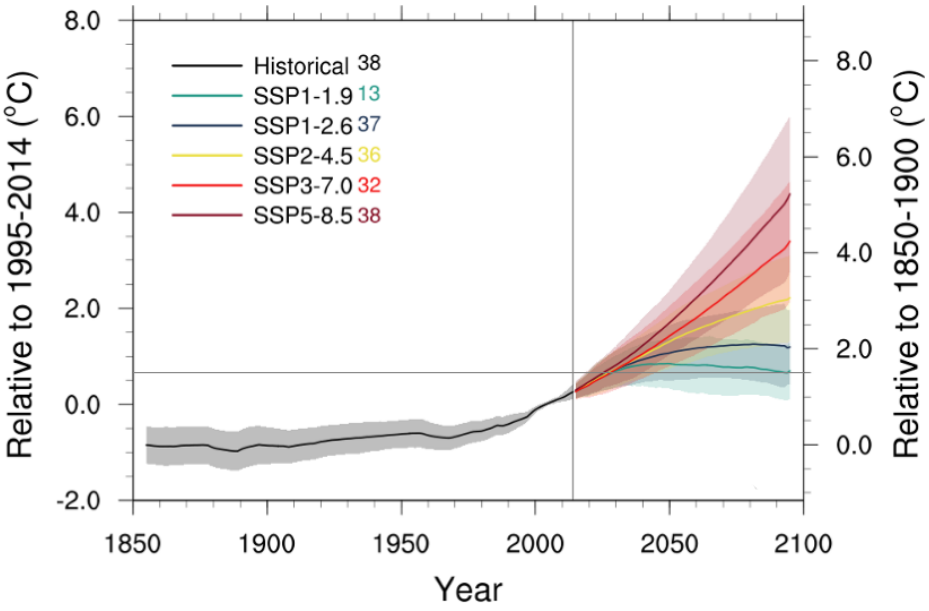


Figure 1. Global 11-year running averages of temperature changes from current baseline (1995–2014, left axis) and pre-industrial baseline (1850–1900, right axis). Greenhouse gas emission scenarios: SSP1-1.9, very low; SSP1-2.6, low; SSP2-4.5, intermediate; SSP3-7.0, high; SSP5-8.5, very high. Details see Appendix B.1. The graph is from Tebaldi and colleagues [27] with a horizontal line added at 1.5 °C, the threshold of the Paris Agreement.

COP28 should have addressed this foreseeable failure: it was the first meeting to take stock, that is, to assess each countries' promised contribution and the collective progress towards the 1.5 °C goal [28].Yet, the stocktake document does not give this assessment, but elaborates on pathways for staying below 1.5 °C (details in Appendix B.5). It thus establishes the presupposition that this was still possible and that the COPs provide the politically most pragmatic conference format [29]. However, in physical reality, the COPs and the Paris Agreement should be considered as insufficiently pragmatic, as the following historical account suggests.

The foreseeable failure to stay below 1.5 °C—for which many are to blame—is not surprising. In 2018, the IPCC estimated that, in the scenario of net zero in 2050, surpassing 1.5 °C had a one-third chance of occurring, but nations have bet against this occurrence (details in Appendix B.6). Before 2008, scientists already predicted that the 1.5 °C limit would be exceeded with near certainty even if in 2005 no more greenhouse gas was emitted, and that 1 °C could be dangerous [30]. These fears have come to fruition, with a 1 °C of warming reached in 2022 and already proving catastrophic [31]. Therefore, Spash [32] was right when he characterised the Paris Agreement as unrealistic from its inception, a deficiency that underscores the need for improved decision-making and decisive action.

The destruction of living nature [33] presents an even more severe crisis because people vitally depend on ecosystems [34,35]. Moreover, we can consider humanity to have a moral obligation to protect nature [36]. However, in 2022, COP15 concerning biodiversity mainly stated targets [37], failed to be explicit about important issues [38], and did not mention root causes, so 'this deal may force us to reconsider the usefulness of such meetings altogether' [39].

2.2. Decision-Making by the United Nations

Despite failures to make effective decisions, the decision model has always remained essentially unchanged, with the United Nations (UN) maintaining the exclusive right to decide on global affairs at COPs [40] and the Summit of the Future [41]. However, the member states' interests jeopardise effective joint decisions because there is a custom that each state can issue a veto at the COPs, though the president may decide otherwise ([42], p. 228). Also, politics may deform scientific findings, such as those presented by the IPCC [43], or be unprepared for their implications [44]. Moreover, corporations exert great influence on global governance [45]. Indeed, among the 100,000 attendants of COP28 [46], there were 2456 lobbyists from the fossil fuel industry [47] and 34 billionaires [48]. Additionally, the president of COP28 was the chief executive of the host country's oil company, which is determined to increase oil production capacity by 25% between 2020 and 2030 [49].

2.3. Systems Approach

It is not only an improvement of the decision model that is needed (as argued above), but also a systems approach to the world's many crises, such as climate change [50], global inequality [51], and the threat of nuclear war [52], most of which are related [53].

To clarify the notions of systems (or systemic) approach and system change, we first define a system. A system is a set of globally aligned moral or formal rules that are agreed by parties or imposed by institutions, along with the objects or structures subjected to these rules. Examples include international trade (a worldwide monetary economy), the UN (for global governance), and the International Criminal Court (for international jurisdiction). System change, also called transformational change, is understood as the purposeful transformation of the (global) system (details in Appendix B.7). We consider this system as consisting of interdependent subsystems and schematically represent their change as a single event to be decided upon. A systems approach involves addressing root causes (fundamental change) and system-wide suppressing or adapting to problems. Resolving root causes is vital because problems may resurface if only their manifestations

('symptoms') are combatted; also, there may not be sufficient resources to suppress all manifestations in isolation. For example, a cause of global warming is the emission of greenhouse gas, for which a root cause is overconsumption; pinpointing more fundamental causes requires reconsideration of goals ([54], Box 1). An example of system change that only suppresses a problem's manifestation is capturing CO_2 from the atmosphere to reduce global warming when this greenhouse gas is still emitted. System-wide adaptation is illustrated by large-scale introduction of air conditioning against heatwaves.

There is no shortage of rational proposals for systemic solutions. Those regarding the collapse of nature and resource depletion date back to the seventies and recognise the combination of human population growth and an unsustainable economy [55–57]. However, the past half-century has not witnessed the implementation of system changes, with measures instead addressing the manifestations rather than the root causes of problems. The UN, in particular, lacks a systemic approach: It addresses climate change, biodiversity loss, and desertification at different COPs, and its sustainable development goals are invitations to a fragmented approach ([58], p. 67).

2.4. Global Governance

The inadequacy of both the decision model and problem approach can be summarised as insufficient global governance. We define governance as the continuous coordination of common affairs by individuals and private or public institutions. The concept of governance has been posited in Western science to remedy the failures of the state and the free market. This definition of governance originates from the more elaborate definition by the Commission on Global Governance [59]; according to 'scholars from various countries', governance as theory should 'challenge' the traditional authority of the state and the government [60]. Yet, hierarchical governance, such as the nation-state and supranational authority, remains the subject of investigation ([61], pp. 207, 213). We consider governance as the process (not the result) of repeated decision-making and as part of system change. The importance of global governance has been underscored in several studies. Indeed, there has been an exponential growth in the number of publications on policy analysis of global problems between 2003 and 2021, covering topics such as environmental degradation, energy supply, and pandemics [62]. We now give an impression of the problems with global governance because these problems could also be present when deciding on system change.

The UN, the European Union, and many other international institutions are judged to be 'incapable of rising to the challenges' and even the concept of the nation-state is found to be in 'deep crisis' [63]. Causes of insufficient international governance are the short-term economic and political interests of the nations, and a lack of hard enforcement mechanisms, leading to free-riding, that is, not complying with an agreement while others do [64]. Also, international governance suffers from fragmentation, which is defined as the presence of 'multiple and often overlapping institutions and actor constellations active in the same area, and the resulting normative conflicts'. The governance of global socio-ecological systems, from climate to biodiversity, is fragmented most. There are more than a thousand multilateral agreements in this domain. This absence of overarching institutions is partly explained by two phenomena: first, the overlapping constituencies prefer incremental changes, and second, governments create weak and underfunded organisations as a form of 'symbolic policymaking' that does not infringe upon their national sovereignty [65].

The world is also governed by a broad but loosely aggregated non-governmental polity that crosses nation borders, because more than 99% of international organisations do not have nation states as their members (details in Appendix B.8). An example is the Forest Stewardship Council. These transnational institutions are also plagued by free-riding, the lack of hard enforcement mechanisms ([66], pp. 174, 177) and fragmentation ([67], p. 16). As Micklethwait and Wooldridge [68] put it, by now there are 'more checks than balances'.

Additionally, politicians, the public, academia, and other organisations fiercely compete to change opinions, at least in parliamentary democracies; moreover, voters accept or reject information based on their predispositions ([69], pp. 418, 422). This competition not only adds randomness to national and international decision-making, but also reinforces itself because the only possible short-term response is to join the competition.

Other problems reinforce themselves as well, thus creating another obstacle to the improvement of global governance. Hale and Held [70] identify the following causes of such gridlock: non-cooperation, fragmentation, increasing problem complexity, and multipolarity (rise of new powers and proliferation of actors). They point out that gridlock inflicts harm, leading to nationalism, which in turn reinforces non-cooperation at the international level, thus closing the feedback loop. Another feedback loop exists: the failure of states and the biophysical collapse reinforce each other [53].

Yet other causes of insufficient global governance are deficiencies of democracy, legitimacy, accountability, conflict resolution, and effectiveness [71]. A more thorough analysis of these causes would be the task of global governance experts who (as we propose) would help to design a method for deciding on system change.

2.5. Alternative Global Governance

A wide range of solutions has been advocated to address inadequate global governance, such as assemblies of randomly chosen world citizens [72,73], world federalism [74], and political argumentation regarding so-called wicked problems [75]. Reform of UN conferences is another option [63,76] but its chance of success thus far is estimated to be no more than one fifth [77].

Unfortunately, no effective procedure to decide on such initiatives exists. This deficit can be seen as Buchanan's meta-coordination problem for global institutions (details in Appendix B.9). The present essay seeks to address the meta-coordination problem for system change, that is, the problem of designing an institution that designs system change. More specifically, the main research question is: *how should a procedure for deciding on the required system change be designed?* Contained in the 'how' should be the answers to four subsidiary questions: First: who should design? (Answered in Section 4). Second: how should the decision-making procedure be evaluated? (In Appendix A.2 we suggest a verification group.) Third: who monitors the design process? (Suggestions are also in Appendix A.2). Fourth: what is the method to make the meta-decision, that is, to decide how to design the decision-making procedure? (In Appendix A.1 we suggest scoring as one example). We now consider how the main question has been answered before.

3. Meta-Decision Structures

Various organisations and other structures exist that help to select a procedure for deciding on specific global affairs, such as climate change, but not explicitly on system change. These meta-decision structures are briefly reviewed here to demonstrate the novelty and relevance of our proposal for allowing decision-making experts and others to form this structure.

One meta-decision structure is provided by academia. Orlove and colleagues [78] reviewed research papers on decision-making for climate change and identified interesting trends but made no recommendations to improve decision-making and did not consider the need for fundamental change (details in Appendix B.10). Another example is the Earth System Governance Project, which initiated a proposal for UN reform [76]. This project continued to explore global governance during its October 2023 conference, which was 'designed to have an impact also beyond the event itself' [79]. Extending this goal much further, we propose that a conference (or other procedure) should actually lead to a decision on global governance and other system change, and that decision-making experts should design this procedure.

The Global Challenges Foundation pursues 'the development of decision systems that can better and more accurately minimize, and preferably eliminate, the major global threats to humanity'. It held a public contest for ideas and selected the best development proposals by jury [80,81]. Unfortunately, the selection method was not publicised and the prizes alone were insufficient to let the winners implement their proposals at scale. One of the winning proposals is elaborated in a book on global governance. In a section on its history, the authors imagine a gathering similar to the Dublin deliberations about a world constitution. They conclude that reform should target the UN because 'it is what we have' [63].

The Stimson Center has proposed that the UN creates an expert advisory group and holds a world summit on 'Inclusive Global Governance' no later than September 2023, with the 'chief aim of re-designing and better equipping the global governance system' [82]. A drawback of this programme is that experts only provide advice (rather than directives) about the global governance system, with the UN unlikely to adopt any advice to change the governance system substantially. Indeed, the UN postponed a similar initiative for a summit in September 2023 with the unfortunate predicate 'of the future' [83].

These findings suggest that few other meta-decision structures exist and that their outcomes often lead back to the UN. However, the UN cannot and should not be expected to decide on global ecological security ([84], pp. 413–414), let alone on even more fundamental issues. Therefore, the question remains: Whose job is it to decide on system change? The answer could be given within the following meta-decision structure.

4. Decision-Making Experts

Designing a procedure for deciding on system change is a complex task which, in principle, is best left to decision-making experts, that is, scientists and practitioners. Therefore, we propose that *independent experts in collective decision-making, including design processes and problem analysis, design a procedure for decisions on the required system change.* The design process should be monitored by auxiliary bodies; we suggest such bodies for verification, overview, and argumentation (for details, see Appendix A.2). These decision-making experts should not make decisions about system change, but instead, should use their expertise and research to design a procedure that allows others to make those decisions. For example, in 2010, experts selected the (conditionally) best voting procedure [85]; in some settings, a decision tree can aid this selection [86].

Designing a decision-making procedure for global change is more demanding than choosing a voting procedure. Indeed, decision theory and related areas cover vast fields of theory and expertise, as summarised in Table 1. This list of areas should also include relevant elements of politicology, sociology, psychology, anthropology, and organisation theory (focusing on bureaucracy). In particular, it should consider problem analysis, goal setting, and opportunities for a shift of paradigm or mindset ([54], Box 1), possibly through unconventional modes of thinking [87,88]. Experts in information and communication technology should be involved at an early stage, for instance, to build an architecture for collecting and processing system-change proposals. As the decision-making experts only decide on a procedure by which others decide, they should not contribute to knowledge of the subject matter, for example, energy supply. The theory of (normative) ethics is another example because at this stage, no particular mindset is advocated, although the decision-making experts would have to indicate the role of ethics in the decision-making procedure (examples of such roles are in Appendix A.3, paragraph about contents).

These experts will also need to indicate the role of strategy: should participants in the decision-making process contribute to a system-change design that withstands obstruction by vested interests, while still being innovative? Or should the experts change the present programme so that it gains legitimacy? The necessary strategic expertise will be sketched in Section 7.3 of the discussion.

Table 1. Fields of decision-making theory.

Concise Descriptions of Some Important Fields of Decision-Making Theory
Social-choice theory is concerned with the aggregation of judgements or preferences, such as through various voting procedures [89–91]. To illustrate, an impossibility theorem states, loosely speaking, that no procedure for collective decision-making can recognise 'objective basic needs or universal criteria' [92].
Public-choice theory considers decision-makers to be self-interested agents, as in an economy [93].
Multiple-attribute group decision-making [94].
Global governance [95], defined as repeated decision-making.
Decision-making based on wisdom, knowledge and reason. For governance, this is known as noöcracy [96], epistocracy [97,98], or epistemic democracy [99], and more generally, as collective reasoning [100].
Negotiation [101] and the theory of mathematical games, including mechanism design [102].
Deliberation, such as in citizens' assemblies, comprising randomly selected citizens who inform themselves and decide collectively, often subject to group dynamics [103,104].
Representation and delegation [105,106].
Argumentation theory, that is, logic, rhetoric, and public discourse [107,108].
Analytical methods, such as cost-benefit analysis [109].
Individual decision-making and its fallacies [110].

5. Design of a Decision-Making Procedure

As explained in previous sections, deciding on system change requires decision change—the design of a new procedure to decide on system change. The programme to achieve these changes consists of three stages (Figure 2).

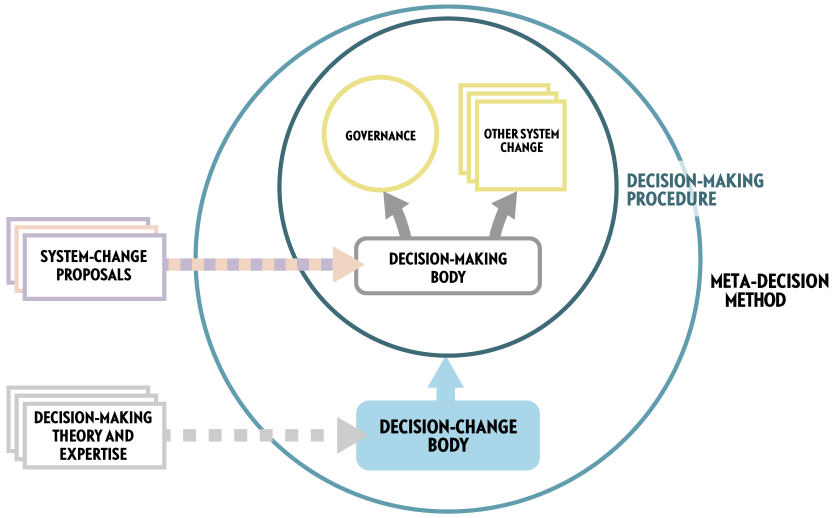


Figure 2. The programme for decision and system change. Box with rounded corners, group of people; solid arrow, a group's output; dashed arrow, a group's input; pile of paper, information; circle and (solid) arrows in that circle, decision-making procedure. For example, 'other system change' may consist of prescriptions for a new economy. For copyright, see acknowledgements.

Design: Independent experts in collective decision-making design a one-time decision-making procedure (medium-sized circle), while being monitored by auxiliary bodies (suggestions in Appendix A.2). The decision-making experts and auxiliary bodies are collectively called the decision-change body (lower box). Designing a decision-making procedure basically is a process of deciding how to decide, which follows a meta-decision

method (larger circle and the upward arrow protruding from the lower box). This method is also to be selected by the experts, who already possess the required expertise and theoretical understanding, such as social-choice theory (lower dashed arrow). Suggestions for the meta-decision method are in Appendix A.1.
Collection of system-change proposals: If unprepared, the decision-making body would possess only a limited array of system-change proposals and be faced with the daunting task of inventing additional proposals from the start. Therefore, proposals would have to be collected in advance to provide a head start, after which more proposals can be added (upper dashed arrow). Although this step should actually be designed by the decision-making experts, it has been inserted to show the experts that proposals will be available to decide upon.
Decision: The decision-making body (upper box) employs the decision-making procedure designed by the decision-change body. Using system-change proposals (upper dashed arrow), the decision-making body decides on issues such as an economy based on wellbeing indicators ('other system change') as well as governance (that is, repeated decision-making), which may differ from the decision-making procedure used for its selection.

The following formal reasoning makes plausible that the decision-making procedure for system change is likely to process a variety of proposals and arguments adequately. First, the procedure (medium-sized circle) is probably well-founded because A. it is based on decision-making theory and expertise (lower dashed arrow); B. this information is processed well, since the design process (lower upward arrow) is safeguarded by auxiliary bodies. To guarantee independency of the decision-change body, these auxiliary bodies should not, for example, admit representatives of UN member states to the process of designing a decision-making procedure. Second, the resulting decision on system change is likely to be a trade-off between effectiveness and fairness (to deal with shortages) because A. many system-change proposals are submitted and arguments are advanced (upper dashed arrow); B. as just shown, the decision-making procedure probably is well-founded, so it may adequately process these considerations. For example, it is unlikely that the conclusion of the decision-making experts is to have any of the UN member states play a decisive role (as with the COPs) in the decision on system change.

6. Coordination

The decision- and system-change programme must be conducted by a global team, shown in the outer left circle in Figure 3. The continuity of the team should be guaranteed by an existing (or perhaps new) public or private organisation that is independent in the sense that its (political, ideological, or commercial) purpose does not essentially interfere with the programme. The team has to complete the following, entirely administrative tasks.

A Compose the decision-change body (at the left of the rectangle); that is, convene independent experts in collective decision-making and assemble the auxiliary bodies. For details about independency, see Appendix A.2, second point. The decision-change body designs a procedure (box with a slit) to collectively decide on system change.
B Collect initial system-change proposals from experts in relevant subject areas, not only as a head start, but also to convince decision-making experts to participate by making it plausible that their decision-making procedure will be implemented.
C Collect proposals and other input from the public. (At least, this is our suggestion: Appendix A.3, paragraph about content.) Box C represents the inputs from both the decision-making body and other parties.
D The decision-making body should combine the proposals and other input according to the selected decision-making procedure. The team only needs to initiate this final stage, that is, ensure that it is organised.

The result of this programme would be a system-change design. In the most optimistic scenario, its implementation keeps the earth habitable.

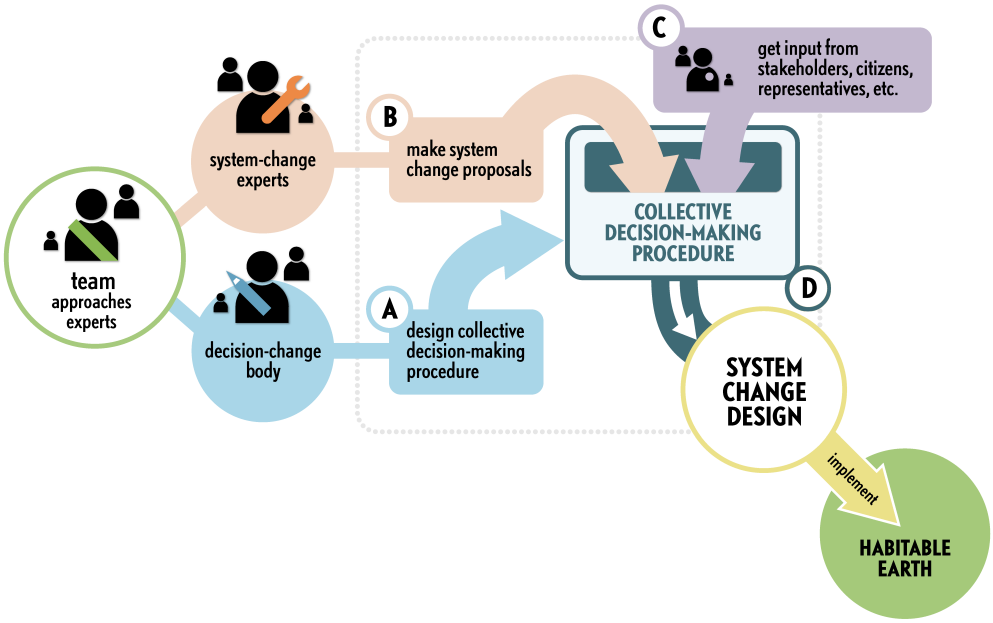


Figure 3. Coordination of the programme. The programme comprises four main steps (A, B, C and D) and is coordinated by a team. For copyright, see acknowledgements.

7. Discussion

To summarise, as global crises intensify, the need for a procedure to decide on system change becomes increasingly urgent. Independent experts in collective decision-making, including design theory and problem analysis, should design this decision-making procedure; various auxiliary bodies must safeguard the design process; proposals for system change should be collected; and with the aid of the procedure, a decision is to be taken on system change. These steps are collectively referred to as the programme for decision and system change. Notably, the experts do not design actual changes but a procedure by which others decide on system change.

In this section, we evaluate the proposed programme. In Appendix A, we give ideas for implementation of the programme's components. With these considerations we only intend to indicate that the programme is worth an attempt. Estimating the success probability of this attempt would require more research into social-change processes.

7.1. Potential Advantages of the Programme

Legitimacy is discussed first. In his work on meta-coordination views, Buchanan ([111], pp. 59–60) lists various views on legitimacy in terms of conditions and proposes five general conditions. We use these to determine whether the decision-making body would be perceived as legitimate. First, comparative benefit, which certainly is present in the long run, considering our predicament. Second, institutional integrity, which means that the institution does what it should do; indeed, the decision-making body would deliver a system-change design. Third, minimal moral acceptability, such as the respect for rights: this depends on the severity of the necessary measures. Fourth, acceptable origination, which is the case because the design of the decision-making procedure and body is 'through an appropriate process' and a variety of system-change proposals is collected, as we clarified at the end of Section 5. Fifth, soundness of the procedure: disagreeable outcomes have a chance of being the result of fair instead of corrupted decision-making (see next paragraph). Which of these conditions need to be met depends on how compelling the purpose of the new institution is ([112], pp. 299, 308) or how badly any old institution functions ([111], p. 60). We conclude that a large fraction of the population might give authority to the decision-making body.

The decision-making procedure would probably suppress conflicts of interest. During design of the decision-making procedure, there might already be conflicts of interest because the organisation that backs the team cannot be entirely independent (politically, ideologically, or commercially), even if it is financed by other organisations. Nevertheless, the decision-change body would be able to design a procedure to decide on system change that is as resistant to conflicts of interest as possible.

Lastly, there is a chance that the programme leads to fundamental change because a wide range of proposals may reveal less well-known mechanisms that obviate the need for some traditional concepts; we give an illustration of such a mechanism in Appendix A.4.

7.2. Potential Limitations of the Programme

The decision-making experts would need to decide themselves on the precise structure and the procedure of the decision-change body. First, a decision on the meta-decision method is left to them, that is, they would have to decide how to decide how to decide. This decision would be informal; Appendix A.1 lists some options for the meta-decision method (composition and leadership of the team of decision-making experts, scoring). Second, the experts would have to informally agree on the auxiliary bodies and how one of them monitors the other; Appendix A.2 gives starting-points for their definition.

Further, despite the presence of auxiliary bodies, decision-making experts may be suspected of promoting or ignoring certain interest groups, or of approaching decision-making too technically.

Additionally, the programme might be misinterpreted as a decision on system change instead of a decision on decision-making, or decision-making experts might be confused with expert decision makers, that is, with experts in a subject matter who make decisions ('technocrats'). In particular, experts in governance could be tempted to propose specific forms of global governance rather than indicate how to decide on this topic and other system change.

Finally, the definition of auxiliary bodies, a meta-decision method, and other administrative details of the decision-change body may render the programme too complex for timely implementation, especially if further theorised on instead of flexibly put to practice. This, however, does not preclude an immediate start of the programme.

7.3. Implementation Prospects

Implementation of the necessary systemic change, whether designed according to the proposed programme or not, may meet socio-political obstacles, just like measures within the present system. Unfortunately, research into socio-political obstacles is itself obstructed by an 'opaque mix of rarely discussed, mutually reinforcing professional interests, norms, and power-structures' [113]. Nevertheless, we mention two obstacles to underscore that the programme would have to develop strategies to manage them or rather avoid their creation.

First, the changes may not be easy for the global population to endure, even when the measures and the decision-making procedure have a clear rationale that is published in reputable sources, and citizens participate in decision-making. For example, halting combustion of fossil fuels and biomass may decimate the energy supply. Whether such measures would create wide-spread opposition is hard to predict from complex single-case studies of climate change [114] or from polarisation within society [115,116].

In addition, vested interests such as industry and politics may try to obstruct measures that result from system change, in particular, system change to secure the environment [117]. Many anti-environmentalist groups and currents have been distinguished [118,119]. For sake of this exposition, we divide their methods in two categories. First, material methods, such as the creation of financial dependency (for example, petro-universities [120]) and shifting the responsibility for taking action to others [121]. Second, informational methods, that is, propaganda and debate, for which a large arsenal of methods exists (details in Appendix B.11). In this category, the counter-measures are of the same kind: information [122]. For a more general approach to power and social change, the decision-change

or decision-making body shall have to select from several theories of power, many of which are being debated [123].

The outcome is uncertain. It would therefore seem more pragmatic to accept present-day decision-making, such as the COPs, as a more or less accomplished fact, and to try to convince decision makers of the necessary changes by publications, petitions, protests, and personal communications. However, as the stocktake of COP28 illustrated, the effectiveness of these actions can be an illusion because attention is diverted. So, probably the only effect of such actions will be that 'the presuppositions of the system are being reinforced by the limits put on the range of the debate' ([124], p. 234). If current world politics is accepted, that system will continue to serve short-term interests and inevitably lead to a ghastly future [125]. Thus, there is need for the design of a new procedure to decide on system change, however uncertain its outcomes.

8. Conclusions and Call to Action

Global crises, such as climate change and ecological collapse, largely reflect ineffective decision-making at a global level. There currently is no meaningful focus on system change to stimulate fundamental or global transformations, including the declaration of a planetary state of emergency. We therefore questioned *how a procedure for deciding on the required system change should be designed.*

Alternative global decision-making procedures (such as world federalism) have garnered insufficient support. Meta-decision structures to decide on such alternatives (for example, academia) have not been completely successful and are not focusing on decision-making for system change.

We propose an improved meta-decision structure: *Let independent experts in collective decision-making, including design processes and problem analysis, design a procedure to decide on the required system change.* Auxiliary bodies would then be placed to protect the design process against pitfalls. The programme of decision and system change is defined as the design of a decision-making procedure ('decision change') followed by the collection of system-change proposals and the actual decision on system change. Notably, the experts do not decide on system change themselves. We argued that the decision-making body may be perceived as legitimate and that it may engender system change despite the opposition that is to be expected.

A single, global team, supported by an independent organisation, should conduct this programme. *We call on individuals to form such a team and on independent organisations to support its formation.* The team can facilitate decision change as a first step to system change that will hopefully keep the earth habitable.

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Abbreviations

The following abbreviations are used in this manuscript:

COP	Conference of the Parties
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change
NDC	Nationally Determined Contribution
UN	United Nations
UNFCCC	UN Framework Convention on Climate Change

Appendix A. Potential Pathways

We have described the meta-decision method, auxiliary bodies, decision-making procedure, and system-change design abstractly. In this appendix, we give some ideas for implementation of these abstract components, although the specifics of the programme's outcome will differ in a given implementation.

Appendix A.1. The Meta-Decision Method

The design of the decision-making procedure has been considered part of the meta-decision; that is, the decision on how to decide on, or design, system change. Decision-making experts select the meta-decision method, giving due consideration to the following. The experts should have a range of backgrounds and opinions (that is, be cognitively diverse) to generate good ideas for a decision-making procedure. During implementation ('coordination'), they may lose the 'common ground' for the selection of a procedure due to divergent expression of meanings, so-called discursive diversity; that can be reduced by allowing the experts to align their meanings, in particular when aided by a team leader [126]. In addition, experts may be inclined to compete and reach a conclusion that is inferior to a result arrived at cooperatively; this so-called Apollo effect can be reduced (though not avoided completely) by varying, for example, the composition of a team and the selection of a team leader [127]. To aggregate judgements, the experts can list properties of the decision-making procedure, for example, legitimacy [95,128], and score them such that only the scoring precision depends on the number of proponents. A simple example of scoring is to let each expert first assign weights to the properties (yielding average weights) and then score the properties of each procedure, where the end scores are the average ([94], § 3.2.1).

Appendix A.2. Safeguarding the Design Process

Auxiliary bodies should monitor the design process to protect against common pitfalls beyond the above-mentioned weaknesses of the meta-decision method. Decision-making experts should determine the structure and composition of these bodies at the start of the programme. (This is not formalised further.) The team should allow these bodies to evolve no longer than a predetermined moment to guarantee checks and balances thereafter.

We suggest three auxiliary bodies as starting points: the verification group, the overview board, and the argumentation council.

First, the decision-making experts may fall victim to increasing confirmation bias, which has been called the 'spiral of conviction' by Friedman [129]. To correct for this, a verification group could verify (simulate or comment on) the proposed decision-making procedure. This can provide democratic feedback, forcing 'technocrats to contend with information that their procedures deemed irrelevant' [130]. An imperfect example that comes close to the intended feedback can be seen when a Dutch citizens' assembly proposed an amendment to the Lower Chamber election procedure in 2006 [103,131,132]. Actually, this event illustrates how lay people alone re-designed the details of a decision-making procedure.

Second, an overview board could ensure that the design process continues as specified. Decision-making experts, unlike technocrats, do not make the final decision, but they do determine the type of decision maker. This renders them vulnerable to 'political maneuvering' [130] and to loss of independency. The board should be able to only

accept decision-making experts who are independent and vice versa, insist that missing knowledge is included. To meet these requirements, the overview board might comprise professional supervisors and journalists.

This leads to the third auxiliary body. If unchecked, the overview board could have excessive power to manipulate the programme, though other bodies may also use the design process strategically. Terms that express ethical positions are particularly prone to misuse. On the one hand, they may be used to conceal the disadvantages of a decision procedure or other component and stifle dissenting voices; on the other hand, the vocabulary used to analyse such improper use [32,108,133] can be misused equally well, for example, to obstruct any appeal to ethics. An argumentation council could seek to prevent such improper use of the design process. Based on consistency and completeness alone and not on the subject matter, the council should approve any verdict by the overview board, any exposition of the proposed decision-making procedure, and other important arguments. To these ends, the council should consist of experts in argumentation theory and professional editors.

The argumentation council would not have to be controlled by a fourth body: The decision-making experts need to cooperate since ultimately, the quality of their decision-making procedure determines whether the public gives authority to the decision-making body.

Appendix A.3. Decision-Making Procedures

To provide an idea of possible decision-making procedures, we now consider a few aspects regarding the decision-making body, content, and rules.

One idea is to let a variety of people participate, as for reform of organisations [134]. For system change, the decision-making body could comprise diverse people: scientists and other problem-specific experts, corporate executives, artists, randomly chosen citizens, and representatives of diverse entities. These entities might include nations, indigenous peoples, non-governmental organisations, future generations [135], and nature animate and even inanimate [136]. A fundamental approach will also necessitate reconsidering goals that may be unattainable because of the problems at hand, such as perpetual economic growth as an end in itself [137]. Philosophers and experts on religious or secular world views can assist in reconsidering goals and purposes. We use the vague notion of a habitable earth as a representative goal, but an alternative objective might be to accept global system collapse and handle the ensuing emergencies [138].

As to the content: The proposals and insights of such a variety of people can best be processed if they are mostly submitted in writing. No unconventional or imaginative ideas should be excluded pre-emptively. Events that can be perceived as threats may need to be accepted as measures to avert worse consequences—the so-called trolley problem [139]—or such events may be contemplated further to generate novel ideas. Even when submitted ideas seem unethical or ineffective, it is the decision-making body that judges their ethics and effectiveness. Notably, ethics as such may not only be advocated ([140], p. 556) but also be criticised [141] if only for its improper application [142] or it may be handled by rules of a mechanism or institution (see Appendix A.4 on system-change design below).

Concerning the rules: The decision-making would have to start with a problem analysis. Because the crises are related, *all* major problems should be analysed. This consideration will not complicate but rather facilitate an analysis because the root causes and impact of measures will be identified. Covering a great number of topics and insights is feasible if system-change proposals are initially submitted in writing and processed transparently. The decision-making procedure therefore would have to be formal to a certain extent, for example, be based on a structure that allows to overview and analyse the argumentation. This may restrict the range of candidate decision-making procedures but we are unable to make any suggestions for such a procedure. The decision-change body would have to determine how very many people (as suggested above) or a smaller decision-making body can decide on these proposals. An overview board, as suggested in the section about the meta-decision method, might be indispensible. Finally, the laws of nature and logic may dictate measures that are difficult to bear in the short term. Organisations

and individuals tend to avoid such measures, even if the problems will be unsupportable in the long run. For example, to reduce global warming, the world must stop burning fossil fuels and biomass. Therefore, the resulting decision-making rules must stimulate a bold approach based on courage to acknowledge problems and act accordingly.

Appendix A.4. System-Change Design

System change needs to consist of drastic measures. These probably will not be adopted or imposed effectively, but there can be exceptions: A measure could be proposed that does not require bureaucracies, monitoring, sanctions, coercion, or a shift of mindset for its enactment. A simple example of such a measure (not necessarily part of system change) is fair division of a resource ('cake') among two persons: one person cuts, the other chooses. More generally, such measures can be provided by the discipline of mechanism and institution design. Decentralised mechanisms and institutions exist in which information is dispersed among their participants rather than concentrated in bureaucracies or transformed by parliamentary democracies. The participants directly inform the mechanism or institution, which is designed to produce fair and effective decisions (if possible) where participants cannot profit from misreporting information.

To finish with some background: Out of the debate concerning centralised planning in market socialism [143], a discipline called mechanism and institution design arose. A mechanism is a game to reach some social goal, where a game is a construct in which participants freely behave 'on the basis of their preferences and strategic considerations'. This information is decentralised, that is, shared among participants (and usually private). These mechanisms can be designed such that participants (collectively) profit the most when *truthfully* reporting their information, a property called (group) strategyproofness, where 'strategy' is conceived as an action unrelated to the content proper. An institution (or institutional arrangement) is mainly understood as an arrangement that imposes the rules (not any measures proper), possibly 'by spontaneous actions of a group where there is no institutional entity in charge of its administration or enforcement' [144]. Mechanism and institution design, often shortened to the ambiguous term 'mechanism design,' has a broader scope than economics; for example, it encompasses social-choice and game theory, as mentioned in Table 1.

Appendix B. Details

Appendix B.1. The Scenario Model Intercomparison Project

In Figure 1, each thick line is the ensemble mean of the outcomes of several models; the number of models is mentioned after the scenario in the legend. The future simulations start at 2015. The shaded areas approximate the 90% confidence intervals for the anomalies with respect to the historical baseline (1995–2014). The lowest emission scenario is 'specifically designed to meet the Paris Agreement target of 1.5 °C warming' and some of its simulations 'have a small [temporary] overshoot of the target, which was expected by the design' [27]. The authors conclude on an accompanying website [145]: 'The 1.5 °C threshold [. . .] is, on average across models, projected to be reached within the current decade no matter the scenario'.

Appendix B.2. The Intergovernmental Panel on Climate Change

Figure 1 is comparable to part (a) of Figure SPM.3 in [146], in which the scenario for the lowest greenhouse gas (GHG) emissions shows an overshoot of 1.5 °C that is only temporary. However, this scenario is based on 'anthropogenic removals of CO_2' without an indication of their likelihood [147].

Appendix B.3. The World Meteorological Organization

The probability has increased (from 24% to 48% to 66%) that the mean annual temperature rises 1.5 °C in the five years following 2020, 2022, and 2023, respectively [148–150].

Appendix B.4. The United Nations Environment Programme and Others

Implementation of Nationally Determined Contributions (NDCs) does not avert an expected temperature increase significantly over 2 °C by the end of this century [151], nor will even the most diligent technical efforts, given increasing energy consumption [152]. References to recent studies on delayed warming were omitted from the present essay.

Appendix B.5. The Global Stocktake

The stocktake document first only stated that the promises as such fell short of keeping global warming below 2 °C. It then continued with descriptions of the pathways that limit warming to 1.5 °C [153] despite the prediction that with 90% probability, 1.5 °C would be reached in 2023 [154] or otherwise, almost certainly briefly after, as we indicated for 2022; notably, between COP27 and COP28, studies were submitted that consider the 1.5 °C goal to be feasible, possibly after a temporary overshoot [155,156]. Whatever the case, the document diverted attention from the insufficiency of the contributions and the transgression of 1.5 °C to the exact wordings and content of the pathways, thus establishing the presupposition that 1.5 °C would still be possible [157] and that the COPs provide the most pragmatic conference format.

Appendix B.6. Betting against a one-third Chance of Failure

The IPCC [158] states: 'All 1.5 °C pathways see global CO_2 emissions embark on a steady decline to reach (near) net zero levels around 2050'. The 'assessment suggests a remaining budget of about 420 $GtCO_2$ for a two-thirds chance of limiting warming to 1.5 °C, which, for the estimated 42 $GtCO_2$ yr^{-1}, would mean net zero in 20 years (that is, in 2038 and not 2028 because at some point, the time lapse is rounded to the next 5 years due to the variation of 15–20 years). The emissions for unconditional NDCs in 2030 are estimated to be 52–58 $GtCO_2e$ yr^{-1} (inter-quartile range) where 'e' is for 'equivalent'. So, the nations bet against approximately a one-third chance of failure to stay below 1.5 °C.

Appendix B.7. System Change

The definition of a system is largely taken from Zapf [50], except for its normative character, which stems from the definition of system change in Waddock ([159], p. 190), as adopted here.

Appendix B.8. International Non-Governmental Organisations

The number of international governmental organisations stabilised at 350 in 1990 ([160], Figure 2) while in 2023 approximately 42,000 international organisations were active. Their number increases by about 1200 each year [161] so the percentage of non-governmental organisations nears 100%. Notably, at least at the national level, the boundary between governmental and non-governmental organisations is blurred because 'governments collaborate with private organizations to form public-private hybrids, delegate public standard-setting, and outsource services to private corporations' [162].

Appendix B.9. The Meta-Coordination Problem

The meta-coordination problem is the question 'how to converge on public standards that institutions are to meet' [163], that is, 'how to decide' which institution 'we should coordinate our behaviour around' [164]. (An institution is conceived as a legitimised organisation.) In this essay, the institution would not deal with regular governance but would design system change.

Appendix B.10. Orlove's Classification

The classification by Orlove and colleagues [78] of adaptation as a fundamental change is not adopted here because adaptation, as opposed to mitigation, addresses the manifestations of a problem rather than its causes.

Appendix B.11. Informational Anti-Environmentalist Methods

We divide the informational methods of 'climate obstruction' in three types. First, indoctrination, as in education [120]. Second, misinformation, such as greenwashing [121], inattention [122], denial (or more subtly, 'manufacturing uncertainty'), and astroturf campaigns [118]. Third, 'discursive obstruction', for example, demonisation and framing [165]. These obstructions of discourse can be rhetoric [166] or refer to material methods [167,168]. A recent thought-provoking example is The Daily Telegraph [169].

References

1. Climate Carnage: Whose Job Is it to Save the Planet? *The Guardian*, 2022; at 10:52. Available online: https://www.theguardian.com/environment/video/2022/nov/10/climate-carnage-whose-job-is-it-to-save-the-planet-documentary (accessed on 2 February 2024).
2. Rosane, O. "These Processes Are Failing": Greta Thunberg Calls Out World Leaders as Bonn Talks Founder. *Common Dreams*. 14 June 2023. Available online: https://www.commondreams.org/news/thunberg-calls-out-world-leaders-at-bonn (accessed on 2 February 2024).
3. Maslin, M.; Parikh, P.; Taylor, R.; Chin-Yee, S. COP27 Will Be Remembered as a Failure: Here's what Went Wrong. *The Conversation*. 22 November 2022. Available online: https://phys.org/news/2022-11-opinion-cop27-failurehere-wrong.html (accessed on 2 February 2024).
4. McGuire, W. The Big Takeaway from Cop27? These Climate Conferences just Aren't Working. *The Guardian*. 22 November 2022. Available online: https://www.theguardian.com/commentisfree/2022/nov/20/big-takeaway-cop27-climate-conferences-arent-working (accessed on 2 February 2024).
5. Scrutton, A. After a Mediocre Deal, COP27 Needs a Dose of Democracy. *Democracy Notes*. 22 November 2022. Available online: https://www.idea.int/blog/after-mediocre-deal-cop27-needs-dose-democracy (accessed on 2 February 2024).
6. Slavin, T. After "Disappointing" COP27, Calls Grow for New Approach to Fighting Climate Change. *Reuters*. 28 November 2022. Available online: https://www.reuters.com/business/sustainable-business/after-disappointing-cop27-calls-grow-new-approach-fighting-climate-change-2022-11-28/ (accessed on 2 February 2024).
7. Democracy in Europe Movement 2025. COP off! DiEM25's Alternative Climate Conference to COP27. *DiEM Communications*. 14 November 2022. Available online: https://diem25.org/cop-off-diem25s-alternative-climate-conference-cop27/ (accessed on 2 February 2024).
8. Dixson-Declève, S. End the Circus of COP27 Once and for All. *Club of Rome*. 22 November 2022. Available online: https://www.clubofrome.org/blog-post/decleve-cop27/ (accessed on 2 February 2024).
9. Nordborg, H. COP is a Planned Failure: Why Having a Bad Plan Is Worse than Not Having a Plan. *Global Climate Compensation*. 23 November 2022. Available online: https://www.global-climate-compensation.org/p/cop-is-a-planned-failure (accessed on 2 February 2024).
10. Unitarian Universalist Service Committee. COP27: Radical Alternatives Needed. 15 November 2022. Available online: https://www.uusc.org/cop27-radical-alternatives-needed/ (accessed on 2 February 2024).
11. Rockström, J.; Dixson-Declève, S.; Robinson, M.; Ki-moon, B.; Tubiana, L.; Huq, S.; Nobre, C.; Ghosh, A.; Burrow, S.; Patel, S.; et al. Reform of the COP Process. A Manifesto for Moving from Negotiations to Delivery. *Club of Rome*. 23 February 2023. Available online: https://www.clubofrome.org/cop-reform/ (accessed on 2 February 2024).
12. Brandt, U.; Svendsen, G.T. Is the annual UNFCCC COP the only game in town? Unilateral action for technology diffusion and climate partnerships. *Technol. Forecast. Soc. Change* **2022**, *183*, 121904:1–121904:9. [CrossRef]
13. Sommerer, T.; Agné, H.; Zelli, F.; Bes, B. The Legitimacy Crises of the WTO and the UNFCCC. In *Global Legitimacy Crises: Decline and Revival in Multilateral Governance*; Sommerer, T., Agné, H., Zelli, F., Bes, B., Eds.; Oxford University Press: Oxford, UK, 2022; pp. 79–102. [CrossRef]
14. Benedick, R. E. Avoiding Gridlock on Climate Change. *Issues Sci. Technol.* **2007**, *23*, 37–40. Available online: https://jstor.org/stable/43314398 (accessed on 2 February 2024).
15. Hermwille, L.; Obergassel, W.; Ott, H.E.; Beuermann, C. UNFCCC before and after Paris: What's necessary for an effective climate regime? *Clim. Policy* **2017**, *17*, 150–170. [CrossRef]
16. Hjerpe, M.; Nasiritousi, N. Views on alternative forums for effectively tackling climate change. *Nat. Clim. Change* **2015**, *5*, 864–867. [CrossRef]
17. Widerberg, O.; Pattberg, P. International Cooperative Initiatives in Global Climate Governance: Raising the Ambition Level or Delegitimizing the UNFCCC? *Glob. Policy* **2015**, *6*, 45–56. [CrossRef]
18. Dixson-Declève, S. COP28 Did Not Deliver; We Need Better Global Governance and Brave Leadership. *Club of Rome*. 15 December 2023. Available online: https://www.clubofrome.org/blog-post/decleve-post-cop28/ (accessed on 2 February 2024).
19. Monbiot, G. Cop28 Is a Farce Rigged to Fail, but There Are Other Ways We Can Try to Save the Planet. *The Guardian*. 9 December 2023. Available online: https://www.theguardian.com/commentisfree/2023/dec/09/cop28-rigged-fail-save-planet-climate-summit-fossil-fuel (accessed on 2 February 2024).

20. Neslen, A. We Need Power to Prescribe Climate Policy, IPCC Scientists Say. *The Guardian*. 7 December 2023. Available online: https://www.theguardian.com/environment/2023/dec/07/we-need-power-to-prescribe-climate-policy-ipcc-scientists-say (accessed on 2 February 2024).
21. United Nations. Paris Agreement. 2015. Available online: https://unfccc.int/sites/default/files/english_paris_agreement.pdf (accessed on 2 February 2024).
22. Iyer, G.; Cui, R.; Edmonds, J.; Fawcett, A.; Hultman, N.; McJeon, H.; Ou, Y. Taking stock of nationally determined contributions: Continued ratcheting of ambition is critical to limit global warming to 1.5 °C. *One Earth* **2023**, *6*, 1089–1092. [CrossRef]
23. Adger, W.N. Loss and Damage from climate change: Legacies from Glasgow and Sharm el-Sheikh. *Scott. Geogr. J.* **2023**, *139*, 142–149. [CrossRef]
24. Tramel, S. The Road Through Paris: Climate Change, Carbon, and the Political Dynamics of Convergence. *Globalizations* **2016**, *13*, 960–969. [CrossRef]
25. Streck, C.; von Unger, M.; Krämer, N. From Paris to Katowice: Cop-24 Tackles the Paris Rulebook. *J. Eur. Environ. Plan. Law* **2019**, *16*, 165–190. [CrossRef]
26. Sinkovics, N.; Vieira, L. M.; van Tulder, R. Working toward the sustainable development goals in earnest—Critical international business perspectives on designing and implementing better interventions. *Crit. Perspect. Int. Bus.* **2022**, *18*, 445–456. [CrossRef]
27. Tebaldi, C.; Debeire, K.; Eyring, V.; Fischer, E.; Fyfe, J.; Friedlingstein, P.; Knutti, R.; Lowe, J.; O'Neill, B.; Sanderson, B.; et al. Climate model projections from the Scenario Model Intercomparison Project (ScenarioMIP) of CMIP6. *Earth Syst. Dyn.* **2021**, *12*, 253–293. [CrossRef]
28. United Nations Framework Convention on Climate Change. *Views on the Elements for the Consideration of Outputs Component of the First Global Stocktake: Synthesis Report by the Secretariat*; Items I.A.2 and I.A.3.b; 4 October 2023. Available online: https://unfccc.int/sites/default/files/resource/SYR_Views%20on%20%20Elements%20for%20CoO.pdf (accessed on 2 February 2024).
29. Breeze, N. *COPOUT. How Governments Have Failed the People on Climate—An Insider's View of Climate Change Conferences, from Paris to Dubai*; Ad Lib: Woodbridge, UK, 2024; pp. 57, 257.
30. Ramanathan, V.; Feng, Y. On avoiding dangerous anthropogenic interference with the climate system: Formidable challenges ahead *Proc. Natl. Acad. Sci. USA* **2008**, *105*, 14245–14250. [CrossRef]
31. Ripple, W.J.; Wolf, C.; Gregg, J.W.; Rockström, J.; Newsome, T.M.; Law, B.E.; Marques, L.; Lenton, T.M.; Xu, C.; Huq, S.; et al. The 2023 state of the climate report: Entering uncharted territory. *BioScience* **2023**, *73*, 841–850. [CrossRef]
32. Spash, C. This changes nothing: The Paris Agreement to ignore reality. *Globalizations* **2016**, *13*, 928–933. [CrossRef]
33. Díaz, S.; Settele, J.; Brondízio, E.S.; Ngo, H.T.; Guèze, M.; Agard, J.; Arneth, A.; Balvanera, P.; Brauman, K.A.; Butchart, S.H.M.; et al. (Eds.) *Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*; IPBES Secretariat: Bonn, Germany, 2019. [CrossRef]
34. Chapin, F.S.; Zavaleta, E.S.; Eviner, V.T.; Naylor, R.L.; Vitousek, P.M.; Reynolds, H.L.; Hooper, D.U.; Lavorel, S.; Sala, O.E.; Hobbie, S.E.; et al. Consequences of changing biodiversity. *Nature* **2000**, *405*, 234–242. [CrossRef]
35. Managi, S.; Islam, M.; Saito, O.; Stenseke, M.; Dziba, L.; Lavorel, S.; Pascual, U.; Hashimoto, S. Valuation of nature and nature's contributions to people. *Sustain. Sci.* **2022**, *17*, 701–705. [CrossRef]
36. Piccolo, J. J.; Taylor, B.; Washington, H.; Kopnina, H.; Gray, J.; Alberro, H.; Orlikowska, E. "Nature's contributions to people" and peoples' moral obligations to nature. *Biol. Conserv.* **2022**, *270*, 109572:1–109572:8. [CrossRef]
37. Anderson, V.; Read, R. Biodiversity: Targets and Lies. *Resilience*. 20 December 2022. Available online: https://www.resilience.org/stories/2022-12-20/biodiversity-targets-and-lies/ (accessed on 2 February 2024).
38. United Nations. In Proceedings of the Conference of the Parties to the Convention on Biological Diversity: Kunming-Montreal Global Biodiversity Framework, Decision 15/4, 19 December 2022; Targets 16 and 18. Available online: https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf (accessed on 2 February 2024).
39. Büscher, B.; Duffy, R. Biodiversity Treaty: UN Deal Fails to Address Root Causes of Nature's Destruction. *The Conversation*. 12 December 2022. Available online: https://theconversation.com/biodiversity-treaty-un-deal-fails-to-address-the-root-causes-of-natures-destruction-196905 (accessed on 2 February 2024).
40. United Nations. *Our Common Agenda: Report of the Secretary-General*, 2021; Item 62, p. 48. Available online: https://www.un.org/en/content/common-agenda-report/assets/pdf/Common_Agenda_Report_English.pdf (accessed on 2 February 2024).
41. High-Level Advisory Board on Effective Multilateralism. *A Breakthrough for People and Planet: Effective and Inclusive Global Governance for Today and the Future*; United Nations University: New York, NY, USA, 2023; pp. 13, 24. Available online: https://highleveladvisoryboard.org/breakthrough/pdf/56892_UNU_HLAB_report_Final_LOWRES.pdf (accessed on 2 February 2024).
42. Rietig, K.; Peringer, C.; Theys, S.; Censoro, J. Unanimity or standing aside? Reinterpreting consensus in United Nations Framework Convention on Climate Change negotiations. *Int. Environ. Agreements* **2023**, *23*, 221–234. [CrossRef]
43. Rached, D.H. The Intergovernmental Panel on Climate Change: Holding Science and Policy-Making to Account. *Yearb. Int. Environ. Law* **2014**, *24*, 3–36. [CrossRef]
44. Spratt, D.; Armistead, A. COVID-19 Climate Lessons: Unprepared for a Pandemic, Can the World Learn How to Manage the Bigger Threat of Climate Disruption? National Centre for Climate Restoration (Breakthrough). 2020. Available online: https://www.breakthroughonline.org.au/papers (accessed on 2 February 2024).

45. May, C. Who's in charge? Corporations as institutions of global governance. *Palgrave Commun.* **2015**, *1*, 15042:1–15042:10. [CrossRef]
46. McSweeney, R. Analysis: Which Countries Have Sent the Most Delegates to COP28? *Carbon Brief*. 1 December 2023. Available online: https://www.carbonbrief.org/analysis-which-countries-have-sent-the-most-delegates-to-cop28/ (accessed on 2 February 2024).
47. Kick Big Polluters Out. Record Number of Fossil Fuel Lobbyists at COP28. 5 December 2023. Available online: https://kickbigpollutersout.org/articles/release-record-number-fossil-fuel-lobbyists-attend-cop28 (accessed on 2 February 2024).
48. Watts, J. One in Four Billionaire Cop28 Delegates Made Fortunes from Polluting Industries. *The Guardian*. 12 December 2023. Available online: https://www.theguardian.com/environment/2023/dec/12/one-in-four-billionaire-cop28-delegates-made-fortunes-from-polluting-industries (accessed on 2 February 2024).
49. Abu Dhabi National Oil Company Strategy. Available online: https://adnocdrilling.ae/en/innovation-and-growth/strategy (accessed on 2 June 2023).
50. Zapf, M. *Averting Climate Catastrophe Together: Framework for Sustainable Development with a Cooperative and Systemic Approach*; Walter de Gruyter: Berlin, Germany, 2022; pp. 3, 159. [CrossRef]
51. Bucelli, I.; McKnight, A. *Mapping Systemic Approaches to Understanding Inequality and Their Potential for Designing and Implementing Interventions to Reduce Inequality*; Working Paper 62; International Inequalities Institute: London, UK, 2021. Available online: https://www.bosch-stiftung.de/sites/default/files/publications/pdf/2021-05/LSE_working_paper_inequality.pdf (accessed on 2 February 2024).
52. Budjeryn, M. Distressing a System in Distress: Global Nuclear Order and Russia's War against Ukraine. *Bull. At. Sci.* **2022**, *78*, 339–346. [CrossRef]
53. Ahmed, N.M. *Failing States, Collapsing Systems. Biophysical Triggers of Political Violence*; Springer: Cham, Switzerland, 2017; pp. 87, 92, 94. Available online: https://academia.edu/34816514/Failing_States_Collapsing_Systems_BioPhysical_Triggers_of_Political_Violence_SPRINGER_BRIEFS_IN_ENERGY_ (accessed on 2 February 2024).
54. Bolton, M. A system leverage points approach to governance for sustainable development. *Sustain. Sci.* **2022**, *17*, 2427–2457. [CrossRef]
55. Goldsmith, E.; Allen, R.; Allaby, M.; Davoll, J.; Lawrence, S. *A Blueprint for Survival*; Penguin: Harmondsworth, UK, 1977.
56. Heilbroner, R.L. Ecological Armageddon. In *Between Capitalism and Socialism*; Vintage Books: New York, NY, USA, 1970; pp. 269–283.
57. Meadows, D.L. (Ed.) *The Limits to Growth: A Report for the Club of Rome Project on the Predicament of Mankind*; Universe Books: New York, NY, USA, 1972. Available online: https://www.donellameadows.org/wp-content/userfiles/Limits-to-Growth-digital-scan-version.pdf (accessed on 2 February 2024).
58. d'Orville, H. The Relationship between Sustainability and Creativity. *Cadmus* **2019**, *4*, 65–73. Available online: https://cadmusjournal.org/article/volume-4/issue-1/relationship-between-sustainability-and-creativity (accessed on 2 February 2024).
59. Commission on Global Governance. *Our Global Neighborhood*; Oxford University Press: Oxford, UK, 1995. Available online: https://academic.oup.com/book/53430 (accessed on 2 February 2024).
60. Keping, Y. Governance and Good Governance: A New Framework for Political Analysis. *Fudan J. Hum. Soc. Sci.* **2018**, *11*, 1–8. [CrossRef]
61. Weiss, T.G.; Wilkinson, R. Rethinking Global Governance? Complexity, Authority, Power, Change. *Int. Stud. Q.* **2014**, *58*, 207–215. [CrossRef]
62. Yang, Y.; Tan, X.; Shi, Y.; Deng, J. What are the core concerns of policy analysis? A multidisciplinary investigation based on in-depth bibliometric analysis. *Humanit. Soc. Sci. Commun.* **2023**, *10*, 190:1–190:12. [CrossRef]
63. Lopez-Claros, A.; Dahl, A.L.; Groff, M. *Global Governance and the Emergence of Global Institutions for the 21st Century*; Cambridge University Press: Cambridge, UK, 2020; pp. 13, 14, 64, 488. [CrossRef]
64. Frey, U.J.; Burgess, J. Why do climate change negotiations stall? Scientific evidence and solutions for some structural problems. *Glob. Discourse* **2023**, *13*, 138–162. [CrossRef]
65. Biermann, F.; van Driel, M.; Vijge, M.J.; Peek, T. Governance Fragmentation. In *Architectures of Earth System Governance: Institutional Complexity and Structural Transformation*; Biermann, F., Kim, R.E., Eds.; Cambridge University Press: Cambridge, UK, 2020; pp. 165–168; glossary p. 322. [CrossRef]
66. Hale, T.; Held, D. Gridlock and Innovation in Global Governance: The Partial Transnational Solution. *Glob. Policy* **2012**, *3*, 169–181. [CrossRef]
67. Biermann, F.; Pattberg, P.; van Asselt, H.; Zelli, F. The Fragmentation of Global Governance Architectures: A Framework for Analysis. *Glob. Environ. Politics* **2009**, *9*, 14–40. [CrossRef]
68. Micklethwait, J.; Wooldridge, A. The Fourth Revolution: Reinventing the State and Democracy for the 21st Century. *New Perspect. Q.* **2014**, *31*, 24–29. [CrossRef]
69. Friedman, J. Beyond cues and politicial elites: The forgotten Zaller. *Crit. Rev.* **2012**, *24*, 417–461. [CrossRef]
70. Hale, T.; Held, D. Breaking the Cycle of Gridlock. *Glob. Policy* **2018**, *9*, 129–137. [CrossRef]
71. Marx, A.; Wouters J. (Eds.) *Global Governance*; Elgaronline: Cheltenham, UK, 2018. [CrossRef]

72. Bedsted, B.; Mathieu, Y.; Leyrit, C. (Eds.) *World Wide Views on Climate and Energy from the World's Citizens to the Climate and Energy Policymakers and Stakeholders*; Danish Board of Technology Foundation, Missions Publiques, and the French National Commission for Public Debate: Copenhagen, Denmark, 2015. Available online: https://climateandenergy.wwviews.org/wp-content/uploads/2015/09/WWviews-Result-Report_english_low.pdf (accessed on 2 February 2024).
73. Curato, N.; Chalaye, P.; Conway-Lamb, W.; De Pryck, K.; Elstub, S.; Morán, A.; Oppold, D.; Romero, J.; Ross, M.; Sanchez, E.; et al. Global Assembly on the Climate and Ecological Crisis: Evaluation Report; Center for Deliberative Democracy on Global Governance: University of Canberra: Canberra, Australia, 2023. Available online: https://researchprofiles.canberra.edu.au/en/publications/global-assembly-on-the-climate-and-ecological-crisis-evaluation-r (accessed on 2 February 2024).
74. Deese, R.S. *Climate Change and the Future of Democracy*; Springer: Cham, Switzerland, 2019. [CrossRef]
75. Crowley, K.; Head, B.W. The enduring challenge of 'wicked problems': Revisiting Rittel and Webber. *Policy Sci.* **2017**, *50*, 539–547. [CrossRef]
76. Biermann, F.; Abbott, K.; Andresen, S.; Bäckstrand, K.; Bernstein, S.; Betsill, M.M.; Bulkeley, H.; Cashore, B.; Clapp, J.; Folke, C.; et al. Navigating the Anthropocene: Improving Earth System Governance. *Science* **2012**, *335*, 1306–1307. [CrossRef]
77. Browne, S. *UN Reform. 75 Years of Challenge and Change*; Edward Elgar: Northampton, MA, USA, 2019; p. 204.
78. Orlove, B.; Shwom, R.; Markowitz, E.; Cheong, S.-M. Climate decision-making. *Annu. Rev. Environ. Resour.* **2020**, *45*, 271–303. [CrossRef]
79. Earth System Governance. Radboud Conference on Earth System Governance. Bridging Sciences and Societies for Sustainable Transformations. 2023. Available online: https://www.earthsystemgovernance.org/2023radboud/ (accessed on 2 February 2024).
80. Global Challenges Foundation. Joint Campaign to Strengthen International Cooperation Launches Call for Ideas. 26 July 2019. Available online: https://web.archive.org/web/20230327192831/https://globalchallenges.org/joint-campaign-to-strengthen-international-cooperation-launches-call-for-ideas/ (accessed on 2 February 2024).
81. Global Challenges Foundation. New Shape Prize Library. 2018. Available online: https://globalchallenges.org/new-shape-library/ (accessed on 2 February 2024).
82. Stimson Center. UN 2.0: Ten Innovations for Global Governance. 2020; pp. 60–62. Available online: https://www.stimson.org/wp-content/uploads/2020/06/UN2.0-Ten-Innovations-for-Global-Governance-Final.pdf (accessed on 2 February 2024).
83. United Nations General Assembly. Modalities for the Summit of the Future. Document A/RES/76/307. 8 September 2022. Available online: https://digitallibrary.un.org/record/3987340/files/A_RES_76_307-EN.pdf?ln=en (accessed on 2 February 2024).
84. Mische, P.M. Ecological Security and the Need to Reconceptualize Sovereignty. *Alternatives* **1989**, *14*, 389–427. [CrossRef]
85. Laslier, J.-F. And the loser is … plurality voting, 2011. In *Electoral Systems: Paradoxes, Assumptions, and Procedures*; Felsenthal, D.S., Machover, M., Eds.; Springer: Berlin/Heidelberg, Germany, 2012; pp. 327–351. Available online: https://hal.science/hal-00609810/file/cahier_de_recherche_2011-13.pdf (accessed on 2 February 2024).
86. de Almeida, A.T.; Nurmi, H. A Framework for Aiding the Choice of a Voting Procedure in a Business Decision Context. In *Outlooks and Insights on Group Decision and Negotiation*; GDN 2015. Lecture Notes in Business Information Processing; Kamiński, B., Kersten, G., Szapiro, T., Eds.; Springer: Cham, Switzerland, 2015; Volume 218. [CrossRef]
87. Gunster, B. *Omdenken: The Dutch Art of Flip-Thinking*; King Perryman, C., Translator; Lev: Amsterdam, The Netherlands, 2016.
88. Moore, M.-L.; Milkoreit, M. Imagination and transformations to sustainable and just futures. *Elementa* **2020**, *8*, 081:1–081:17. [CrossRef]
89. Arrow, K.A.; Sen, A.; Suzumura, K. (Eds.) *Handbook of Social Choice and Welfare*; Elsevier/North-Holland: Amsterdam, The Netherlands, 2001.
90. Brams, S.J. *Mathematics and Democracy. Designing Better Voting Systems and Fair-Division Procedures*; Princeton University Press: Princeton, NJ, USA, 2008. Available online: https://www.jstor.org/stable/j.ctt7sxc5 (accessed on 2 February 2024).
91. Moulin, H. *Axioms of Cooperative Decision Making*; Cambridge University Press: Cambridge, UK, 1988. [CrossRef]
92. Amadae, S. M. Impossibility Theorem. In Encyclopedia Britannica Online; Abella, J., Anderson, M., Anderson M., Ascierto, J., Ashburn, D., Bigelow, F., Chabot, M., Charboneau, Y., Chmielewski, K., Daly, J., et al., Eds.; Encyclopædia Britannica: Chicago, IL, USA, 2015. Available online: https://www.britannica.com/topic/impossibility-theorem (accessed on 2 February 2024).
93. Rowley, C.K.; Schneider, F. *The Encyclopedia of Public Choice*; Springer: New York, NY, USA, 2003. Available online: https://link.springer.com/book/10.1007%2Fb108558 (accessed on 2 February 2024).
94. Kabak, Ö.; Ervural, B. Multiple attribute group decision making: A generic conceptual framework and a classification scheme. *Knowl. Based Syst.* **2017**, *123*, 13–30. [CrossRef]
95. Ansell, C.; Torfing, J. (Eds.) *Handbook of Theories of Governance*, 2nd ed.; Edward Elgar: Cheltenham, UK; Northampton, MA, USA, 2022; pp. 433, 611. [CrossRef]
96. Laks, A. *Plato's Second Republic: An Essay on the Laws*; Princeton University Press: Princeton, NJ, USA, 2022; p. 19. [CrossRef]
97. Vandamme, P.-E. What's wrong with an epistocratic council? *Politics* **2019**, *40*, 90–105. [CrossRef]
98. Tushnet, M. Democratic remedies if ignorance threatens democracy. In *Democratic Failure*; Schwartzberg, M., Viehoff, D., Eds.; New York University Press: New York, NY, USA, 2021; pp. 262–270. [CrossRef]
99. Rothstein, B. Epistemic democracy and the quality of government. *Eur. Politics Soc.* **2019**, *20*, 16–31. [CrossRef]
100. Mercier, H.; Landemore, H. Reasoning is for arguing: Understanding the successes and failures of deliberation. *Political Psychol.* **2012**, *33*, 243–258. [CrossRef]

101. Courtois, P.; Tazdaït, T. Coopération sur le climat: Le mécanisme de négociations jointes. *Négociations* **2012**, *2*, 25–42. [CrossRef]
102. Wood, P.J. Climate Change and Game Theory: A Mathematical Survey. *Ann. N. Y. Acad. Sci.* **2011**, *1219*, 153–170. [CrossRef]
103. de Jongh, M.S. Group Dynamics in the Citizens' Assembly on Electoral Reform. Ph.D. Thesis, Utrecht University, Utrecht, The Netherlands, 2013. Available online: https://dspace.library.uu.nl/handle/1874/275018 (accessed on 2 February 2024).
104. van Stokkom, B. Deliberative rituals: Emotional energy and enthusiasm in debating landscape renewal. In *Politics and the Emotions: The Affective Turn in Contemporary Political Studies*; Hoggett, P., Thompson, S., Eds.; Continuum Press: New York, NY, USA, 2012; pp. 41–58. [CrossRef]
105. Landemore, H. *Open Democracy: Reinventing Popular Rule for the Twenty-First Century*; Princeton University Press: Princeton, NJ, USA, 2021. [CrossRef]
106. Tangian, A. *Mathematical Theory of Democracy*; Springer: Berlin/Heidelberg, Germany, 2014. [CrossRef]
107. van Eemeren, F.H.; Garssen, B.; Krabbe, E.C.W.; Snoeck Henkemans, A.F.; Verheij, B.; Wagemans, J.H.M. *Handbook of Argumentation Theory*; Springer: Dordrecht, The Netherlands, 2014. [CrossRef]
108. Whyte, J. *Crimes against Logic: Exposing the Bogus Arguments of Politicians, Priests, Journalists, and Other Serial Offenders*; McGraw-Hill: New York, NY, USA, 2017; pp. 75, 153.
109. Dittrich, R.; Wreford, A.; Moran, D. A survey of decision-making approaches for climate change adaptation: Are robust methods the way forward? *Ecol. Econ.* **2016**, *122*, 79–89. [CrossRef]
110. Gilboa, I. *Making Better Decisions*; Wiley-Blackwell: Chichester, UK, 2011.
111. Buchanan, A. Institutional Legitimacy. In *Oxford Studies in Political Philosophy*; Sobel, D., Vallentyne, P., Wall, S., Eds.; Oxford University Press: Oxford, UK, 2018; Volume 4, pp. 53–78. [CrossRef]
112. Adams, N.P. Legitimacy and institutional purpose. *Crit. Rev. Int. Soc. Political Philos.* **2020**, *23*, 292–310. [CrossRef]
113. Lahsen, M.; Turnhout, E. How norms, needs, and power in science obstruct towards sustainability. *Environ. Res. Lett.* **2021**, *16*, 025008:1–025008:10. [CrossRef]
114. Köpke, S. Interrogating the Links between Climate Change, Food Crises and Social Stability. *Earth* **2022**, *3*, 577–589. [CrossRef]
115. Falkenberg, M.; Galeazzi, A.; Torricelli, M.; Di Marco, N.; Larosa, F.; Sas, M.; Mekacher, A.; Pearce, W.; Zollo, F.; Quattrociocchi, W.; et al. Growing polarization around climate change on social media. *Nat. Clim. Change* **2022**, *12*, 1114–1121. [CrossRef]
116. Geiß, S.; Magin, M.; Jürgens, P.; Stark, B. Loopholes in the Echo Chambers: How the Echo Chamber Metaphor Oversimplifies the Effects of Information Gateways on Opinion Expression. *Digit. Journalism* **2021**, *9*, 660–686. [CrossRef]
117. Geels, F.W. Regime Resistance against Low-Carbon Transitions: Introducing Politics and Power into the Multi-Level Perspective. *Theory Cult. Soc.* **2014**, *31*, 21–40. [CrossRef]
118. Brulle, R.J.; Dunlap, R.E. A Sociological View of the Effort to Obstruct Action on Climate Change. *Footnotes* **2021**, *49*. Available online: https://www.asanet.org/sociological-view-effort-obstruct-action-climate-change (accessed on 2 February 2024).
119. White, D.F.; Rudy, A.; Wilbert, C. Anti-Environmentalism: Prometheans, Contrarians, and beyond. In *Sage Handbook in Environment & Society*; Pretty, J., Ball, A.S., Benton, T., Guivant, J.S., Lee, D.R., Orr, D., Pfeffer, M.J., Ward, H., Eds.; Sage: Los Angeles, CA, USA, 2007; pp. 124–141. Available online: https://www.researchgate.net/publication/277007692 (accessed on 2 February 2024).
120. Eaton, E.M.; Day, N.A. Petro-pedagogy: Fossil fuel interests and the obstruction of climate justice in public education. *Environ. Educ. Res.* **2020**, *26*, 457–473. [CrossRef]
121. Blythe, J.; Silver, J.; Evans, L.; Armitage, D.; Bennett, N.J.; Moore, M.-L.; Morrison, T.H.; Brown, K. The Dark Side of Transformation: Latent Risks in Contemporary Sustainability Discourse. *Antipode* **2018**, *50*, 1206–1223; risks 1 and 2. [CrossRef]
122. Lewandowsky, S. Climate Change Disinformation and How to Combat It. *Annu. Rev. Public Health* **2021**, *42*, 1–21. [CrossRef]
123. Avelino, F. Theories of power and social change: Power contestations and their implications for research on social change and innovation. *J. Political Power* **2021**, *14*, 425–448. [CrossRef]
124. Chomsky, N. The Common Good. In *How the World Works*; Chomsky, N., Barsamian, D., Naiman, A., Eds.; Hamish Hamilton: London, UK, 2011; pp. 206–314.
125. Bradshaw, C.J.A.; Ehrlich, P.R.; Beattie, A.; Ceballos, G.; Crist, E.; Diamond, J.; Dirzo, R.; Ehrlich, A.H.; Harte, J.; Harte, M.E.; et al. Underestimating the Challenges of Avoiding a Ghastly Future. *Front. Conserv. Sci.* **2021**, *1*, 615419:1–615419:10. [CrossRef]
126. Lix, K.; Goldberg, A.; Srivastava, S.M.; Valentine, M.A. Aligning Differences: Discursive Diversity and Team Performance. *Manag. Sci.* **2022**, *68*, 8430–8448. [CrossRef]
127. Gershkov, A.; Schweinzer, P. Dream teams and the Apollo effect. *J. Mech. Inst. Des.* 2021, *6*, 113–148. [CrossRef]
128. Davis, J.W. A critical view of global governance. *Swiss Political Sci. Rev.* **2012**, *18*, 272–286. [CrossRef]
129. Friedman, J. *Power without Knowledge: A Critique of Technocracy*; Oxford Academic: New York, NY, USA, 2019; p. 213. [CrossRef]
130. Cole, M. What's Wrong with Technocracy? *Boston Rev.* 22 August 2022. Available online: https://www.bostonreview.net/articles/whats-wrong-with-technocracy/ (accessed on 2 February 2022).
131. Parlementair Documentatie Centrum. Minister Ollongren Presenteert Voorstellen tot Hervorming Parlementair Stelsel. 1 July 2020. Available online: https://www.parlement.com/id/vl9zdaltm4y3/nieuws/minister_ollongren_presenteert (accessed on 2 February 2024).
132. Parlementair Documentatie Centrum. Burgerforum Kiesstelsel. Available online: https://www.parlement.com/id/vhnnmt7ltkw7/burgerforum_kiesstelsel (accessed on 2 February 2024).

133. Fleming, D. Icon. In *Lean Logic: A Dictionary for the Future and How to Survive It*; Fleming, D., Chamberlin, S., Eds.; Chelsea Green: White River Junction, VT, USA, 2016; pp. 204–206. Available online: https://leanlogic.online/glossary/icon-the/ (accessed on 2 February 2024).
134. Weisbord, M.; Janoff, S. *Future Search: Getting the Whole System in the Room for Vision, Commitment, and Action*; Berrett-Koehler: San Francisco, CA, USA, 2010.
135. Tonn, B.E. The future of futures decision making. *Futures* **2003**, *35*, 673–688. [CrossRef]
136. Burgers, L.E. Justitia, the People's Power and Mother Earth. Democratic Legitimacy of Judicial Law-Making in European Private Law Cases on Climate Change. Ph.D. Thesis, University of Amsterdam, Amsterdam, The Netherlands, 2020. Available online: https://dare.uva.nl/search?identifier=0e6437b7-399d-483a-9fc1-b18ca926fdb5 (accessed on 2 February 2024).
137. Organisation for Economic Co-operation and Development. *Beyond Growth: Towards a New Economic Approach, New Approaches to Economic Challenges*; OECD Publishing: Paris, France, 2020; p. 15. Available online: https://read.oecd-ilibrary.org/economics/beyond-growth_33a25ba3-en (accessed on 2 February 2024).
138. Portail de Collapsologie. Better Understand the Current Risks of Social and Environmental Collapses. Available online: https://collapsologie.fr/en/ (accessed on 2 February 2024).
139. Woollard, F.; Howard-Snyder, F. Doing vs. Allowing Harm, 7 July 2021. In *Stanford Encyclopedia of Philosophy*; Zalta, E.N., Nodelman, U., Eds.; Metaphysics Research Lab: Stanford, CA, USA, 2002. Available online: https://plato.stanford.edu/entries/doing-allowing/ (accessed on 2 February 2024).
140. Gardiner, S.M. Ethics and Global Climate Change. *Ethics* **2004**, *114*, 555–600. [CrossRef]
141. Schröder, W. *Moralischer Nihilismus. Radikale Moralkritik von den Sophisten bis Nietzsche*; Reclam: Stuttgart, Germany, 2005.
142. Wright, J.C.; Pölzler, T. Should morality be abolished? An empirical challenge to the argument from intolerance. *Philos. Psychol.* **2022**, *35*, 350–385. [CrossRef]
143. Heilbroner, R.L. Reflections on the future of socialism. In *Between Capitalism and Socialism*; Vintage Books: New York, NY, USA, 1970; pp. 79–114.
144. Hurwicz, L. Economic design, adjustment processes, mechanisms, and institutions. *Econ. Des.* **1994**, *1*, 1–14. Available online: https://link.springer.com/article/10.1007/BF02716611 (accessed on 2 February 2024).
145. Energy Exascale Earth System Model. CMIP6's Scenario-Based Temperature and Precipitation Projections. 26 May 2021. Available online: https://e3sm.org/cmip6s-scenario-based-temperature-and-precipitation-projections/ (accessed on 2 February 2024).
146. Pörtner, H.-O.; Roberts, D.C.; Tignor, M.; Poloczanska, E.S.; Mintenbeck, K.; Alegría, A.; Craig, M.; Langsdorf, S.; Löschke, S.; Möller, V.; et al. (Eds.) *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2022; pp. 8, 16–17. [CrossRef]
147. Masson-Delmotte, V.; Zhai, P.; Pirani, A.; Connors, S.L.; Péan, C.; Berger, S.; Caud, N.; Chen, Y.; Goldfarb, L.; Gomis, M.I.; et al. (Eds.) *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2021; pp. 12, 15. [CrossRef]
148. World Meteorological Organization. United in Science 2020: A Multi-Organization High-Level Compilation of the Latest Climate Science Information; Figure 2, 2020; p.16. Available online: https://library.wmo.int/idurl/4/57145 (accessed on 2 February 2024).
149. World Meteorological Organization. United In Science 2022: A Multi-Organization High-Level Compilation of the Most Recent Science Related to Climate Change, Impacts and Responses. Summary. 2022. Available online: https://library.wmo.int/idurl/4/58075 (accessed on 2 February 2024).
150. World Meteorological Organization. Global Annual to Decadal Climate Update. Summary. 2023. Available online: https://library.wmo.int/idurl/4/68235 (accessed on 2 February 2024).
151. United Nations Environment Programme.Broken Record. Temperatures Hit New Highs, yet World Fails to Cut Emissions (again). Item 7, 2023; p. XXII. Available online: https://www.unep.org/resources/emissions-gap-report-2023 (accessed on 2 February 2024).
152. Rothenberg, G. A realistic look at CO_2 emissions, climate change and the role of sustainable chemistry. *Sustain. Chem. Clim. Action* **2023**, *2*, 100012:1–100012:5. [CrossRef]
153. United Nations Framework Convention on Climate Change. *First Global Stocktake. Proposal by the President*, Document FCCC/PA/CMA/2023/L.17; Items 18, 21, 25 ff, and 173. 13 December 2023. Available online: https://unfccc.int/sites/default/files/resource/cma2023_L17_adv.pdf (accessed on 2 February 2024).
154. Rohde, R. September 2023 Temperature Update. Berkeley Earth. 11 November 2023. Available online: https://berkeleyearth.org/september-2023-temperature-update (accessed on 2 February 2024).
155. Harmsen, M.; Tabak, C.; Höglund-Isaksson, L.; Humpenöder, F.; Purohit, P.; van Vuuren, D. Uncertainty in non-CO2 greenhouse gas mitigation contributes to ambiguity in global climate policy feasibility. *Nat. Commun.* **2023**, *14*, 2949:1–2949:14. [CrossRef]
156. Dafnomilis, I.; den Elzen, M.; van Vuuren, D. Paris targets within reach by aligning, broadening and strengthening net-zero pledges. *Commun. Earth Environ.* **2024**, *5*, 1–10. [CrossRef]
157. United Nations. COP28 Ends with Call to 'Transition Away' from Fossil Fuels; UN's Guterres Says Phaseout Is Inevitable. *UN News*. 13 December 2023. Available online: https://news.un.org/en/story/2023/12/1144742 (accessed on 2 February 2024).

158. Masson-Delmotte, V.; Zhai, P.; Pörtner, H.-O.; Roberts, D.; Skea, J.; Shukla, P.R.; Pirani, A.; Moufouma-Okia, W.; Péan, C.; Pidcock, R.; et al. (Eds.) *Global Warming of 1.5 °C: An IPCC Special Report on the Impacts of Global Warming of 1.5 °C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*; Cambridge University Press: Cambridge, UK, 2018; pp. 96, 116. [CrossRef]
159. Waddock, S. Thinking Transformational System Change. *J. Change Manag.* **2020**, *20*, 189–201. [CrossRef]
160. Eilstrup-Sangiovanni, M. Death of international organizations. The organizational ecology of intergovernmental organizations, 1815–2015. *Rev. Int. Organ.* **2020**, *15*, 339–370. [CrossRef]
161. Union of International Associations. *The Yearbook of International Organizations*; Brill: Leiden, The Netherlands, 2023. Available online: https://uia.org/yearbook (accessed on 2 February 2024).
162. Vandenbergh, M.P.; Jonathan, M.; Gilligan, J.M. *Beyond Politics: The Private Governance Response to Climate Change*; Cambridge University Press: Cambridge, UK, 2017; p. xviii. [CrossRef]
163. Buchanan, A. *The Heart of Human Rights*; Oxford University Press: Oxford, UK, 2013; p. 178. [CrossRef]
164. Scherz, A.; Zysset, A. The UN Security Council, normative legitimacy and the challenge of specificity. *Crit. Rev. Int. Soc. Political Philos.* **2020**, *23*, 371–391. [CrossRef]
165. Tindall, D.B.; Stoddart, M.C.J.; Dunlap, R.E. (Eds.) *Handbook of Anti-Environmentalism*; Edward Elgar: Cheltenham, UK; Northampton, MA, USA, 2022. [CrossRef]
166. Fleming, D. How to cheat in an argument. In *Lean Logic: A Dictionary for the Future and How to Survive It*; Fleming, D.; Chamberlin, S., Eds.; Chelsea Green: White River Junction, VT, USA, 2016; pp. xxiii–xxvi. Available online: https://leanlogic.online/how-to-cheat-in-an-argument/ (accessed on 2 February 2024).
167. Lamb, W.F.; Mattioli, G.; Levi, S.; Timmons Roberts, J.; Capstick, S.; Creutzig, F.; Minx, J.C.; Müller-Hansen, F.; Culhane, T.; Steinberger, J.K. Discourses of Climate Delay. *Glob. Sustain.* **2020**, *3*, e17:1–e17:5. [CrossRef]
168. Steinberger, J.K. Struggle for Survival: The Importance of Climate Activism from the Perspectives of Political Economy and Science Communication, 5 October 2021; at 00:41. Available online: https://www.youtube.com/watch?v=2973tOyZ-TA (accessed on 2 February 2024).
169. Grostern, J.; Herrmann, M.; Cooke, P. Revealed: Scale of The Telegraph's Climate Change 'Propaganda'. *DeSmog*. 23 November 2023; Seattle, WA, USA; London, UK, 2023. Available online: https://www.desmog.com/2023/11/23/revealed-scale-of-the-telegraphs-climate-change-propaganda/ (accessed on 2 February 2024).

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Article

Investigating Public Support for the Carbon Generalized System of Preference through the Lens of Protection Motivation Theory and Information Deficit Model

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Abstract: The pressing challenges of climate change require government policy interventions. The carbon generalized system of preference (CGSP) is a novel incentive policy that has tremendous potential to reduce carbon emissions in response to climate change. However, there have been few studies focusing on public support for the CGSP, which is the precondition for its seamless implementation. Drawing on the protection motivation theory and information deficit model, this study presents and empirically validates a holistic theoretical framework in which information (information about climate change and information about the CGSP), threat appraisal (threat vulnerability and threat severity), and coping appraisal (response efficacy, self-efficacy, and response cost) are the factors influencing public support for the CGSP. Survey data of 372 respondents were empirically analyzed using the PLS-SEM method. The results show that threat vulnerability, threat severity, response efficacy, and self-efficacy positively affect public support for the CGSP, while response cost does not influence public support for the CGSP. Information about climate change indirectly influences public support for the CGSP through threat vulnerability and threat severity. Information about the CGSP not only directly affects public support for the CGSP but also indirectly affects public support for the CGSP through response efficacy and self-efficacy. The theoretical framework of this study can serve as a reference for future research on public support for environmental policies. The findings of this study also furnish insights for policymakers to develop feasible strategies for the seamless implementation of the CGSP.

Keywords: carbon generalized system of preference; carbon emission reduction; public support; protection motivation theory; information deficit model

1. Introduction

The continuous increase in carbon emissions has resulted in drastic climate change, which has sparked widespread concerns in all sectors of society [1–3]. In response to climate change, governments worldwide have agreed to protect the environment and reduce pollution and carbon emissions [4–6]. With this aim, many countries have established and enforced various intervention measures and policies, both at the enterprise and individual level [7–10], to reduce carbon emissions [11–15]. Among these, policies associated with personal carbon emission reduction have become more prevalent, as the rise in carbon emissions due to humans' excessive and unsustainable production and lifestyles accounts for a significant portion of total carbon emissions [3,9,16–19].

The carbon generalized system of preference (CGSP) is a novel proposed policy in China that aims at encouraging individual carbon emission reductions [20–22]. It is an incentive mechanism for carbon emission reduction, which can provide rewards to the public's green and low-carbon behaviors via market mechanisms and financial incentives, as well as steer societal participation in energy conservation and decarbonization [23–25].

As of October 2022, 16 provinces and cities in China have introduced special policies or planning practices related to the implementation of the CGSP [26]. The CGSP is regarded to have tremendous potential for mitigating carbon emissions and realizing China's carbon neutrality goal [21,25]. However, unless the public is supportive of a policy, it is unlikely to be implemented successfully [18,27–29]. For instance, a carbon tax is regarded as an efficient policy for reducing carbon emissions, but the public's strong resistance diminishes its efficacy [13,30]. Therefore, to ensure the smooth implementation of the CGSP, it is essential for the government to understand public reaction to this policy and garner public support [24,31–34].

The earliest academic research on the CGSP dates back to Li et al. [35], who briefly introduced the operational mechanism of the CGSP and provided a methodological design to calculate individual emissions reductions, taking a public bicycle project as an example. Subsequently, Huang et al. [36] proposed a carbon emission reduction calculation methodology for subway travel for when the CGSP is implemented. Tan et al. [20] introduced the mechanism design of the CGSP and investigated the public's willingness to engage in the CGSP based on an extended technology acceptance model. Xiao et al. [21] discussed the CGSP's features, essential characteristics, and conditions for its operation. Si et al. [25] constructed an extended technology acceptance model to investigate the public's willingness to participate in the CGSP. However, few studies have focused on public attitudes and inclinations towards the CGSP and discussed the determinants of public support for the CGSP [24]. To enrich our knowledge of the CGSP and contribute to its seamless implementation, the current study attempts to conduct an evidence-based assessment of public support for the CGSP and relevant determinants.

Public support for environmental policies refers to how individuals orient themselves to the government's policies through their attitudes or behaviors [12,15,37,38]. These non-activist pro-environmental behaviors are essential for far-reaching and long-lasting policy implementation [4,24,39–41]. The theory of planned behavior (TPB), the norm activation model (NAM), the value-belief-norm theory (VBN), and the protection motivation theory (PMT) are the most extensively employed theoretical models for explaining pro-environmental behaviors. Among these theories, the PTM highlights that when individuals are confronted with environmental risks, they tend to engage in two cognitive processes, i.e., threat appraisal and coping appraisal [17,42–45]. These two processes not only consider aspects of individual action but also accommodate aspects of collective action in response to climate change [46–48]. As a result, the PMT is thought to provide a more comprehensive prediction of pro-environmental behaviors than the TPB, the NAM, and the VBN, and can add to our existing knowledge about the motivations behind pro-environmental behaviors [17,49–51]. Consequently, the PMT is currently widely used to investigate residents' pro-environmental behaviors and public support for environmental policies [17,52–54]. Consistent with this view, this study employed the PMT as one of our theoretical bases for investigating public support for the CGSP.

Additionally, although the original PMT posits that information on which individuals judge the scale of threats and their ability to confront the threat are prerequisites for their cognitive processes, previous studies seldom incorporate information about threat and coping appraisals to construct holistic theoretical models [44,47,55,56]. Fortunately, the information deficit model (IDM) claims that providing enough information about the issue in question and corresponding countermeasures to bridge the public's knowledge gap is an ideal way to motivate positive actions [57–60]. Thus, an integration of the PMT and IDT would be able to not only capture individuals' cognitive processes, but also explain the relevance of information. Therefore, this study integrates the PMT and IDM to investigate public support for the CGSP and its determinants. Specifically, this study divided the information construct into two dimensions, i.e., information about climate change (IACC) and information about the CGSP (IACGSP), which were considered as potential determinants to construct a novel and holistic theoretical framework. Afterwards, a survey was undertaken

in the CGSP pilot cities in China, and the partial least squares structural equation model (PLS-SEM) method was employed to perform an empirical analysis.

The contributions of this study are fourfold. First, the current study contributes to the emerging literature on the CGSP by providing a holistic theoretical framework to unveil the determinants of public support for the CGSP. Second, the current study expands the PMT's applicability to the context of the CGSP and contributes to the field of public support for environmental policies by constructing a novel theoretical framework that incorporates the PMT and IDM. Third, this study uncovered the influencing mechanism of information on public support for the CGSP, answering the call for investigations into the information–action gap in environmental research. Finally, the findings of this study may better equip policymakers to develop feasible strategies for the smooth implementation of the CGSP.

The remainder of this study is organized as follows: Section 2 provides the theoretical foundation and develops the research hypotheses for this study. Section 3 outlines the research methodology adopted for this study. Section 4 presents the results and Section 5 discusses the research findings. Finally, Section 6 presents the conclusions, implications, limitations, and future directions.

2. Theoretical Foundation and Hypothesis Development

2.1. Theoretical Foundation and Research Framework

Over the past few decades, a growing number of studies have explored the determinants of people's pro-environmental behaviors and public support for environmental policies. With regard to the CGSP, Tan et al. [20] claimed that institutional technical environment, perceived usefulness, and participation risk are significant predictors of public willingness to participate in the CGSP. Lin and Yang [24] discovered that members of the public who possess a pro-low-carbon attitude and a high level of social trust are willing to adopt CGSP. Si et al. [25] affirmed that attitude, environmental concern, perceived usefulness, and personal innovativeness are potent drivers of the public's willingness to participate in the CGSP. However, studies that consider individuals' cognitive processes and their information about the CGSP and corresponding countermeasures are still lacking.

The PMT, which was developed by Rogers [42], was originally used to predict individuals' protective behaviors in response to fear or threats [55,61–64]. Its basic principle is that when individuals are confronted with fear appeals, they tend to engage in two cognitive processes, i.e., threat appraisal and coping appraisal [17,43–45]. According to the PMT, the threat appraisal includes two aspects, i.e., threat severity (TS) and threat vulnerability (TV). The coping appraisal includes three aspects, i.e., response efficacy (RE), self-efficacy (SE), and response cost (RC). The model predicts that these two processes guide individuals' adaptive responses [2,44,52,61]. Although the PMT was initially developed to predict individuals' health-related behaviors, the theory has recently been applied to predict individuals' environment-related behaviors, such as residents' pro-environmental behaviors [48,51,65,66] and public support for environmental policies [17,52,67,68].

However, the original PMT has been criticized for ignoring the importance of the information by which individuals estimate the extent of threats and their capacity to confront the threats [44,47,55,56]. According to the IDM, providing enough information about the issue in question to bridge this knowledge deficit is the best way to motivate the public's positive actions [57,58,68,69]. Thus, individuals must be well informed about climate change prior to accepting responsibility and recognizing the necessity of adjusting their actions to mitigate greenhouse gas emissions [65,70–72]. The influence of information on people's involvement in pro-environmental behaviors has been validated by a plethora of studies [65,73–76]. Increasing evidence suggests that, however, there exists an information–behavior gap, and individuals' internal perceptions seem to work as a mediator in the information–action relationship [16,69,77,78]. Therefore, it is reasonable to assume that the PMT variables would function as a pivotal mediator in the information–behavior gap when investigating public support for the CGSP.

Grounded in this rationale, this study aims to integrate the PMT and IDM to construct a holistic theoretical framework to investigate public support for the CGSP, an area that has attracted scant attention in the existing literature. Specifically, the current study conceptualized information as a two-dimensional variable (i.e., IACC and IACGSP), as the public not only needs to know the threats associated with climate change, but also needs to be aware of the information about the CGSP that aims to help them cope with such threats. This study proposes that information (i.e., IACC and IACGSP) and the public's threat appraisal (i.e., TS and TV) and coping appraisal (RE, SE, and RC) impact public support for the CGSP. Also, the public's threat appraisal mediates the relationship between IACC and their support for the CGSP, while the public's coping appraisal mediates the relationship between IACGSP and their support for the CGSP. Also, individuals' gender, age, educational level, and monthly income are employed as control variables. The theoretical framework underpinning this study is depicted in Figure 1.

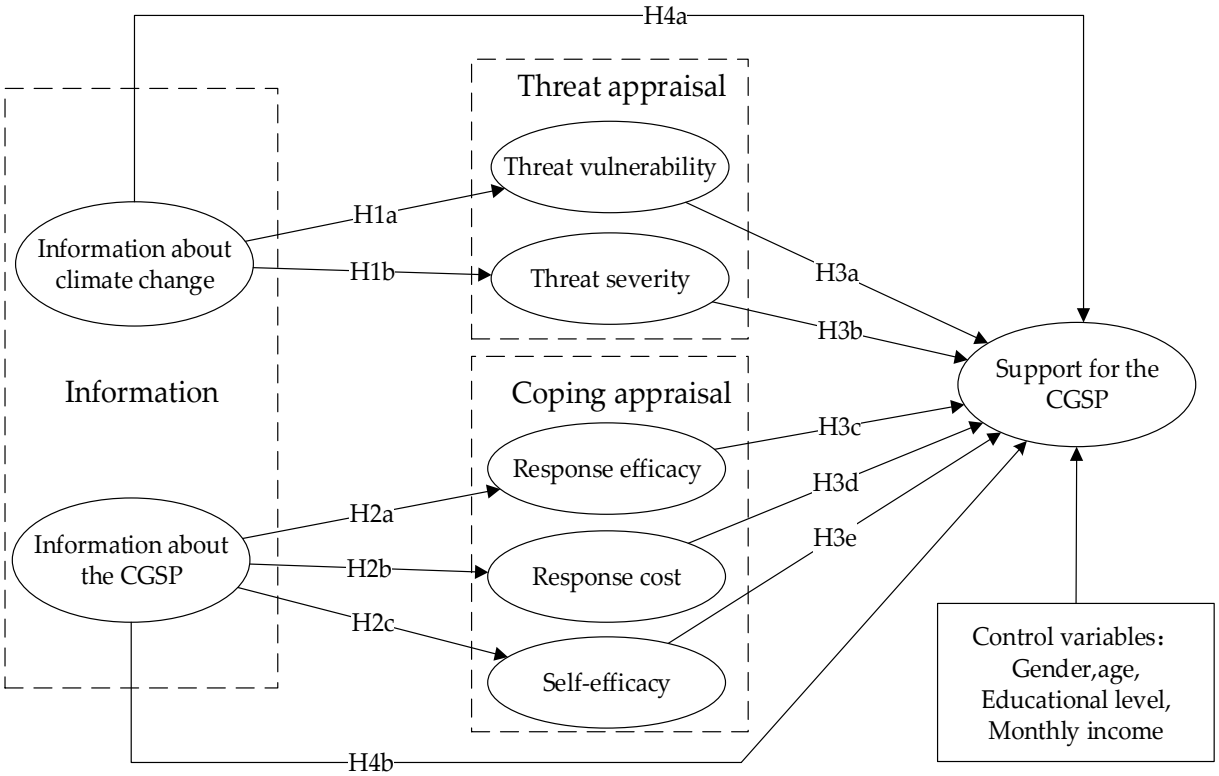


Figure 1. Theoretical framework underpinning this study.

2.2. Hypothesis Development

2.2.1. Information, Threat Appraisal, and Coping Appraisal

According to the IDM, correcting public knowledge deficiencies by delivering rich, relevant information about an issue and response actions is a remedy for action procrastination [57,79,80]. In this regard, the dissemination and accessibility of information about environmental issues and corresponding countermeasures are essential for the public's engagement in pro-environmental behaviors and support for environmental policies [59,73,75]. In this study, IACC refers to the public's access to information about the threats associated with climate change. When individuals receive more IACC, they tend to form a greater perception of threats [69,77]. For instance, Dietz et al. [31] affirmed that IACC is an important antecedent for residents' perceptions of the severity of environmental problems. Dong et al. [69] validated that the abundant provision of IACC would enhance residents' risk perceptions of climate problems, which, in turn, shape their climate actions. Bijani et al. [81] pointed out that IACC is an important antecedent for the threat appraisal process. Based on the above statements, this study predicts that IACC will have positive

effects on the public's threat appraisal process. Consequently, the following hypotheses are put forward:

H1a. *IACC positively influences the public's TS.*

H1b. *IACC positively influences the public's TV.*

In addition to the provision of IACC, information about potential solutions to address the issues in question is also essential [5,82,83]. It is commonly acknowledged that ignorance of countermeasures and ways to implement them is a key obstacle for people to adopt pro-environmental behaviors [72,84]. In this study, IACGSP refers to the public's access to information about the countermeasures contained in the CGSP that can eradicate or reduce the risks related to climate change. The literature has identified that people's knowledge of the possible countermeasures against threats is an important antecedent for them to assess the feasibility of putting them into practice [84,85]. Thus, this study holds that IACGSP will be an important antecedent for those in the coping appraisal process, i.e., RE, SE, and RC. These relationships have been consistently validated by previous studies conducted on public support for environmental policies. For instance, Cismaru et al. [56] claimed that providing information about the steps to reduce greenhouse gas emissions is an effective way to increase residents' self-efficacy and reduce their response costs. Tao et al. [86] documented that action-related information boosts the public's efficacy beliefs, and in turn, their willingness to participate in carbon offset schemes. Xue et al. [47] found that access to climate change information is a crucial antecedent to people's coping appraisal process. Correspondingly, the following hypotheses are put forward:

H2a. *IACGSP positively influences the public's RE.*

H2b. *IACGSP positively influences the public's SE.*

H2c. *IACGSP negatively influences the public's RC.*

2.2.2. Threat Appraisal, Coping Appraisal, and Public Support for the CGSP

Threat appraisal, in the context of environmental studies, denotes one's personal judgement of the hazards caused by environmental problems [17,84]. The fundamental process of threat appraisal is to assess the severity and vulnerability of environmental problems [45]. TS refers to the public's assessment of how seriously they perceive the threat of environmental problems [54,55,87]. In this study, TS can be characterized as the public's perceptions of the seriousness of climate change caused by carbon emissions. The PMT postulates that when individuals are confronted with an environmental threat, they go through the cognitive process of threat appraisal [50,88]. Therefore, if the public thinks that the climate change incurred by carbon emissions is severe, they will be more motivated to support the CGSP. Prior studies evidenced that TS leads to public support for environmental policies. Stoutenborough et al. [89] pointed out that people are more prone to support policies that are meant to solve a problem that entails significant risks. Bockarjova and Steg [17] claimed that PS positively influences drivers' acceptability of policies related to electric vehicles. Hence, the following hypothesis is put forward:

H3a. *TS positively influences public support for the CGSP.*

TV refers to one's judgement of the chance of being exposed to the threat of environmental problems [17]. In this study, TV denotes the public's sensitivity to the risk of climate change. If the public thinks that they are susceptible to suffering from climate change, they may feel compelled to take action to mitigate these threats [54,90]. A plethora of studies have indicated that TV is a potent driver for residents' pro-environmental behaviors and public support for environmental policies. Zobeidi et al. [84] discovered that TV positively

influences farmers' adaptation behaviors to water scarcity as a climate risk. Savari et al. [91] demonstrated that farmers with higher levels of TV are more willing to adopt environmentally responsible behaviors. It is, therefore, plausible to anticipate that public support for the CGSP will increase with higher levels of TV in regards to climate change. This leads to the following hypothesis:

H3b. *TV positively influences public support for the CGSP.*

According to the PMT, coping appraisal includes three factors, i.e., RE, SE, and RC [17,53,77]. RE refers to one's assessment of the perceived effectiveness of adopting a suggested behavior for averting a threat [65,92]. In this study, RE denotes the public's assessment of the perceived effectiveness of CGSP participation in reducing carbon emissions. Generally, people are more prone to engage in pro-environmental behaviors or support environmental policies if they feel their actions can alter the current situation or result in a favorable outcome [52,93]. Pertinent evidence has validated the impact of RE on individuals' pro-environmental behaviors and public support for environmental policies. Lam [52] found that people's views on a certain policy's benefits and effectiveness in addressing climate challenges increase their support for the policy. Wang et al. [50] demonstrated that RE positively shapes farmers' environmental behaviors. Houser et al. [94] affirmed that RE is a crucial motivator for public support for climate adaptation policies. In the context of public support for the CGSP, this study predicts that if the public believes that the CGSP is successful in addressing climate change, they will be more likely to supporting it. This leads to the following hypothesis:

H3c. *RE positively influences public support for the CGSP.*

SE denotes people's perceived capacity to adopt a suggested behavior [84,95]. SE is a crucial determinant to increase people's propensity to support a certain policy. In this study, SE is characterized as the public's assessment of their ability to participate in or support the CGSP. The CGSP is accompanied by an online technological platform [20,21]. Participating in the CGSP not only requires the public to possess this technology, such as the features of carbon currency, but also requires them to understand the rules of its operation, such as the feedback mechanism in achieving carbon emissions goals. If the public lacks the essential competence to accomplish these operations or does not fully grasp these rules, they would not be inclined to support the CGSP. Previous studies have consistently validated the positive relationships between residents' SE and pro-environmental behaviors, as well as SE and public support for environmental policies. Horng et al. [96] claimed that SE is the strongest predictor of tourists' intention to adopt carbon reduction behaviors. Geiger et al. [97] affirmed that SE is the foremost predictor shaping the public discussion about climate change. Juan and Revilla [98] declared that SE is a crucial driver for the enhancement of public support for climate change policies. Thus, the current study predicts that the stronger the public's perceived capability to engage in behaviors related to the CGSP, the more likely the public would support the CGSP. Correspondingly, the following hypothesis is put forward:

H3d. *SE positively influences public support for the CGSP.*

RC refers to how people perceive the expenses of taking protective activities [51]. In this study, RC refers to the cost that the public must bear as a result of participation in the CGSP, which may include time and effort expenditure, discomfort, and even the revelation of personal data. These expenses constantly pose an impediment to motivation and behaviors. According to De Groot et al. [27], residents are more prone to support environmental policies that target low-cost behaviors. Similarly, Pakmehr et al. [99] claimed that RC is the strongest predictor of farmers' adaptation behaviors with regard to water scarcity induced by climate change. Thus, the following hypothesis is put forward:

H3e. *RC negatively influences public support for the CGSP.*

2.2.3. Information and Public Support for the CGSP

The IDM posits that providing enough information about the issue in question to bridge the public's knowledge gap is the best way to motivate positive actions [6,79]. Lack of information is a major barrier to residents' pro-environmental behaviors and the public's support of environmental policies [72,75]. Di Falco and Sharma-Khushal [80] declared that the absence of information was detrimental to ensuring people's adaptive behaviors in regards to climate change. Zobeidi et al. [84] pointed out that residents' information about climate change received from government agencies or the media shapes their pro-environmental behaviors.

Concurrently, research has also linked information about policies with public support policies [30,100]. That is, providing information about the actions required and potential benefits is likely to positively shape public support for environmental policies. According to Rhodes et al. [32], the provision of information regarding the efficacy of low-carbon policies serves as a stimulus for the support of such policies. Moon et al. [1] claimed that a shortage of information about carbon capture and storage impedes public support for corresponding policies. Authelet et al. [85] documented that information about the conservation of ecosystem services in solving threats and gaining benefits can influence both the likelihood and the intensity of people's involvement in a program. Odland et al. [3] claimed that information about decarbonization policies is essential in explaining public support. Thus, the following hypothesis is proposed:

H4a. *IACC positively influences public support for the CGSP.*

H4b. *IACGSP positively influences public support for the CGSP.*

3. Methodology

3.1. Survey Design

The current study's questionnaire consists of three sections. The first section provides a brief explanation of the questionnaire's background and purpose and emphasizes the significance of marking accurate responses in order to reduce hypothetical bias; the second section surveys respondents' demographic information, including gender, age, education, and income; and the third section contains the measurement items corresponding to the eight latent variables. All items on the questionnaire were measured by a 7-point Likert scale, with 1 representing "strongly disagree" and 7 representing "strongly agree" to clearly distinguish respondents' answers [101]. Afterwards, we conducted a pretest with 20 respondents who are familiar with the CGSP and altered several items' descriptions depending on the pretest results and respondents' suggestions. The corresponding measurement items and their sources are presented in Table 1.

Table 1. Measurement items and sources.

Construct	Measurement Items	Sources
Information about climate change (IACC)	IACC1—I can find information about climate change in a variety of ways. IACC2—I believe it is simple to obtain information about climate change. IACC3—I always have prompt access to climate change information. IACC4—I can obtain reliable information about climate change.	[2,47]
Information about the CGSP (IACGSP)	IACGSP1—I can find information about the CGSP in a variety of ways. IACGSP2—I believe it is simple to obtain information about the CGSP. IACGSP3—I always have prompt access to information about the CGSP. IACGSP4—I can obtain reliable information about the CGSP.	[2,47]

Table 1. *Cont.*

Construct	Measurement Items	Sources
Treat severity (TS)	TS1—Climate change has a severely detrimental impact on social well-being. TS2—Climate change has a severely detrimental impact on the living environment. TS3—Climate change has a severely detrimental impact on human health.	[47,56]
Threat vulnerability (TV)	TV1—Environmental pollution can negatively affect me. TV2—I will experience the detrimental impacts of environmental pollution during my lifetime. TV3—I am susceptible to the detrimental impacts of climate change.	[84,91]
Response efficacy (RE)	RE1—Participating in the CGSP can mitigate the detrimental impact of climate change on social welfare. RE2—Participating in the CGSP can reduce the negative impact of climate change on our living environment. RE3—Participating in the CGSP can reduce the negative impact of climate change on the health of humankind.	[45,91]
Self-efficacy (SE)	SE1—It is simple for me to participate in the CGSP. SE2—I am capable of preventing security threats to healthcare information. SE3—I am able to adhere to the recommendations and engage in the actions suggested by the CGSP.	[91,95]
Response cost (RC)	RC1—Taking the steps to participate in the CGSP costs too much money.RC2—Participation in the CGSP takes up a lot of my time. RC3—It is hard for me to act in accordance with the CGSP.	[50,84]
Support for the CGSP (SCGSP)	SCGSP1—I am completely in favor of the CGSP. SCGSP2—I am willing to participate in the CGSP. SCGSP3—I am ready to recommend the CGSP to others.	[29,95]

3.2. Data Collection

The target population of this study is people who are aware of the CGSP, as they are more familiar with the items' meanings and potential supporters of the CGSP. We collected the research data through a web-based survey from China's leading questionnaire website, Questionnaire Star. The reason for utilizing a web-based survey is that the actions to support the CGSP necessitate the public to be familiar with internet technology, such as the exchange procedure of carbon currency. Thus, using a web-based questionnaire to gather data is suitable for the target population of this study. Over a three-week distribution period in December 2022, we finally gathered a total of 512 questionnaires. Then, we removed 140 invalid questionnaires due to their apparent irrationality and contradictory responses. Finally, 372 valid questionnaires were employed for empirical analysis.

The respondents' demographics are displayed in Table 2. Out of all the respondents, the male–female proportion is 1.07, and respondents below the age of 40 account for 72.8%. This distribution is in line with the distribution of general internet users in China [102]. In terms of educational level, most of the respondents have a Bachelor's degree or above, indicating they are capable of actively participating in the CGSP. Concerning monthly income, the majority of respondents have a monthly income under 8000 CNY, which is in line with the income statistics in China [103]. Similar demographics investigating residents' pro-environmental behaviors and public support for environmental policies can be found in prior research [10,25,51]. Overall, the sample of this study is representative.

Table 2. Demographics of the respondents.

Characteristic	Demographic	Frequency	Percentage (%)
Gender	Male	192	51.6%
	Female	180	48.4%
Age (years)	Under 20	31	8.3%
	21–30	126	33.9%
	31–40	114	30.6%
	40–49	74	19.9%
	Over 50	27	7.3%
Educational level	High school and below	38	10.2%
	Junior college	68	18.3%
	Bachelor's degree	189	50.8%
	Master's degree or above	77	20.7%
Monthly income (CNY)	Below 5000	112	30.1%
	5001–8000	143	38.4%
	8000–10,000	64	17.2%
	Over 10,001	53	14.3%

4. Data Analysis and Results

The study utilizes the PLS-SEM method for data analysis. First, PLS-SEMs are confirmed to be appropriate for exploratory analyses and expansive research according to extant theory [104]. This is an exploratory research study that integrates two theories and seven variables that have not been tested in the context of the CGSP. Second, PLS-SEMs have fewer restrictions on sample size and data distribution [105]. The sample size of our study is 372, and the samples do not entirely follow a normal distribution when testing for skewness and kurtosis. As a result, a PLS-SEM was employed for data analysis and hypothesis validation in this study.

There are two kinds of models in an PLS-SEM analysis, i.e., the measurement model and the structural model [106]. The measurement model is utilized to assess the relationship between latent variables and items, whereas the structural model is utilized to investigate the relationships between these latent variables. In the following, we performed the data analysis in two steps. First, the measurement model was assessed by checking the measurement items' outer loadings and assessing the constructs' reliability, internal consistency reliability, and convergent and discriminant validity. Then, the structural model was assessed by calculating the model's R^2 and Q^2 values, which represent the structural model's interpretation power and predictive relevance, respectively, and by validating the proposed hypotheses and their significance [104]. SmartPLS 4 was employed to perform the data analysis [107].

4.1. Measurement Model Evaluation

The measurement model's evaluation was performed as follows. First, the PLS algorithm was employed to compute the measurement items' outer loadings. The results are presented in Table 3. As can be seen, all the items' outer loadings exceed 0.6, suggesting that the items fit well into their measured latent variables [104]. Therefore, no items were excluded from the model. Second, this study rerun the PLS algorithm to test the measurement model's reliability, internal consistency reliability, convergent validity, and discriminant validity. Specifically, the reliability is assessed by the Cronbach's alpha (CA) test; the internal consistency is assessed by the composite reliability (CR); the convergent validity is assessed by the average variance extracted (AVE); and the discriminant validity is evaluated via the Fornell–Larcker criterion, heterotrait–monotrait (HTMT) ratio, and cross loadings. Table 3 shows the CA, CR, and AVE values; Table 4 shows the AVE's square roots and HTMT values; and Table 5 shows the cross loadings.

Table 3. Reliability and validity test.

Construct	Measurement Items	Outer Loadings	Cronbach's Alpha	CR	AVE
IACC	IACC1	0.783	0.771	0.853	0.593
	IACC2	0.744			
	IACC3	0.765			
	IACC4	0.787			
IACGSP	IACGSP1	0.761	0.716	0.823	0.538
	IACGSP2	0.713			
	IACGSP3	0.713			
	IACGSP4	0.746			
TS	TS1	0.862	0.772	0.867	0.685
	TS2	0.808			
	TS3	0.813			
TV	TV1	0.855	0.811	0.888	0.726
	TV2	0.854			
	TV3	0.847			
RE	RE1	0.807	0.733	0.849	0.652
	RE2	0.793			
	RE3	0.823			
SE	SE1	0.814	0.751	0.858	0.668
	SE2	0.808			
	SE3	0.829			
RC	RC1	0.798	0.745	0.854	0.662
	RC2	0.870			
	RC3	0.769			
SCGSP	SCGSP1	0.829	0.783	0.874	0.698
	SCGSP2	0.831			
	SCGSP3	0.846			

Table 4. Discriminant validity test.

Construct	IACC	IACGSP	TV	TS	RE	SE	RC	SCGSP
IACC	0.770	0.676	0.807	0.762	0.705	0.631	0.363	0.705
IACGSP	0.511	0.734	0.812	0.752	0.712	0.832	0.488	0.831
TV	0.642	0.624	0.852	0.687	0.691	0.693	0.398	0.806
TS	0.596	0.567	0.863	0.828	0.703	0.720	0.355	0.793
RE	0.531	0.521	0.534	0.532	0.808	0.808	0.362	0.837
SE	0.482	0.612	0.543	0.551	0.601	0.817	0.351	0.869
RC	0.281	0.368	0.315	0.279	0.269	0.266	0.814	0.385
SCGSP	0.549	0.628	0.643	0.621	0.635	0.668	0.296	0.835

Notes: The square root of the AVE is in bold on the main diagonal. The Fornell–Larcker criterion is below the main diagonal. The heterotrait–monotrait (HTMT) ratio is above the main diagonal.

As can be seen, all the constructs' CA values are within 0.716 and 0.811, and the CR values are within 0.823 and 0.888, exceeding the 0.7 criteria. These results imply that the model has strong reliability and internal consistency [106]. Additionally, all the constructs' AVE values range from 0.538 to 0.726, which surpass the 0.5 criteria, suggesting that the measurement model had a sufficient level of convergent validity [106]. Finally, the square roots of all the constructs' AVE values (bolded values in Table 4) exceed the correlations between them and other constructs [108], all the constructs' HTMT ratios are below 0.9 [109], and all the items' factor loadings are greater than the cross loadings [105]. These results demonstrate that the measurement model has a good level of discriminant validity.

Common method bias may exist in self-reported data taken from the same measurement setting [25]. Harmon's single-factor test is used, and the results show that the variance explained by the first factor is 28.93% (<50%), suggesting that no substantial common method bias affects this investigation [110]. Additionally, the variance inflation factor (VIF) of the measurement items and latent variables is calculated. As a result, all

the VIF values of the measurement items range from 1.122 to 2.369, and all the VIF values of the latent variables range from 1.638 to 2.973. These values are less than the threshold value of 5 [105]. The above results suggest that there is not any significant common method bias or multicollinearity.

Table 5. Cross loadings.

	IACC	IACGSP	TV	TS	RE	SE	RC	SCGSP
IACC1	0.783	0.367	0.494	0.439	0.410	0.379	0.220	0.408
IACC2	0.744	0.390	0.436	0.449	0.374	0.373	0.159	0.392
IACC3	0.765	0.357	0.470	0.429	0.438	0.344	0.214	0.438
IACC4	0.787	0.452	0.567	0.512	0.412	0.387	0.264	0.450
IACGSP1	0.437	0.761	0.537	0.507	0.454	0.503	0.244	0.521
IACGSP2	0.347	0.713	0.387	0.369	0.322	0.467	0.247	0.402
IACGSP3	0.287	0.713	0.419	0.342	0.344	0.391	0.197	0.427
IACGSP4	0.410	0.746	0.474	0.427	0.395	0.429	0.380	0.479
TV1	0.532	0.545	0.855	0.597	0.452	0.445	0.273	0.550
TV2	0.536	0.530	0.854	0.620	0.437	0.471	0.249	0.555
TV3	0.573	0.521	0.847	0.539	0.476	0.471	0.283	0.538
TS1	0.567	0.496	0.612	0.862	0.468	0.475	0.273	0.570
TS2	0.432	0.448	0.499	0.808	0.409	0.421	0.164	0.456
TS3	0.468	0.463	0.585	0.813	0.440	0.469	0.245	0.505
RE1	0.450	0.450	0.466	0.485	0.807	0.460	0.218	0.510
RE2	0.412	0.423	0.402	0.382	0.793	0.488	0.238	0.490
RE3	0.423	0.390	0.425	0.419	0.823	0.508	0.196	0.538
SE1	0.414	0.499	0.418	0.433	0.553	0.814	0.269	0.534
SE2	0.347	0.521	0.403	0.419	0.395	0.808	0.154	0.497
SE3	0.419	0.482	0.506	0.495	0.522	0.829	0.228	0.604
RC1	0.196	0.249	0.214	0.205	0.188	0.196	0.798	0.219
RC2	0.258	0.366	0.310	0.279	0.233	0.248	0.870	0.257
RC3	0.226	0.266	0.232	0.186	0.232	0.199	0.769	0.244
SCGSP1	0.429	0.495	0.507	0.518	0.538	0.528	0.259	0.829
SCGSP2	0.474	0.514	0.556	0.530	0.499	0.564	0.187	0.831
SCGSP3	0.472	0.562	0.547	0.508	0.554	0.581	0.294	0.846

4.2. Structural Model Evaluation

The structural model's evaluation was performed as follows. First, the PLS algorithm was performed to calculate the eight latent variables' R^2 and Q^2 values. The R^2 value shows that the model accounted for 35.4%, 41.1%, 27.0%, 37.3%, 13.3%, and 61.5% of the variance in TS, TV, RE, SE, RC, and SCGSP. Furthermore, the Q^2 values of TS, TV, RE, SE, RC, and SCGSP are, respectively, 0.237, 0.293, 0.170, 0.247, 0.084, and 0.422, which exceed the 0 standard [105]. Consequently, the proposed model has high levels of interpretation power and predictive relevance for public support for the CGSP.

Furthermore, the bootstrapping technique was employed to validate the research hypotheses and mediating effects. The results are shown in Figure 2 and Table 6. Specifically, regarding the relationships in the original PMT, the relationships between the two variables in the threat appraisal and SCGSP are validated. Of the three variables in the coping appraisal, the relationships between RC and SCGSP are not validated. Moreover, IACC has no direct impact on SCGSP, but it can affect SCGSP through TV and TS. IACGSP not only directly affects SCGSP but also indirectly affects SCGSP through RE and SE. As for control variables, the results demonstrate that the path coefficients between gender, age, educational level, monthly income, and SCGSP are all unsupported. These results indicate that demographics do not have any controlling effect on public support for the CGSP.

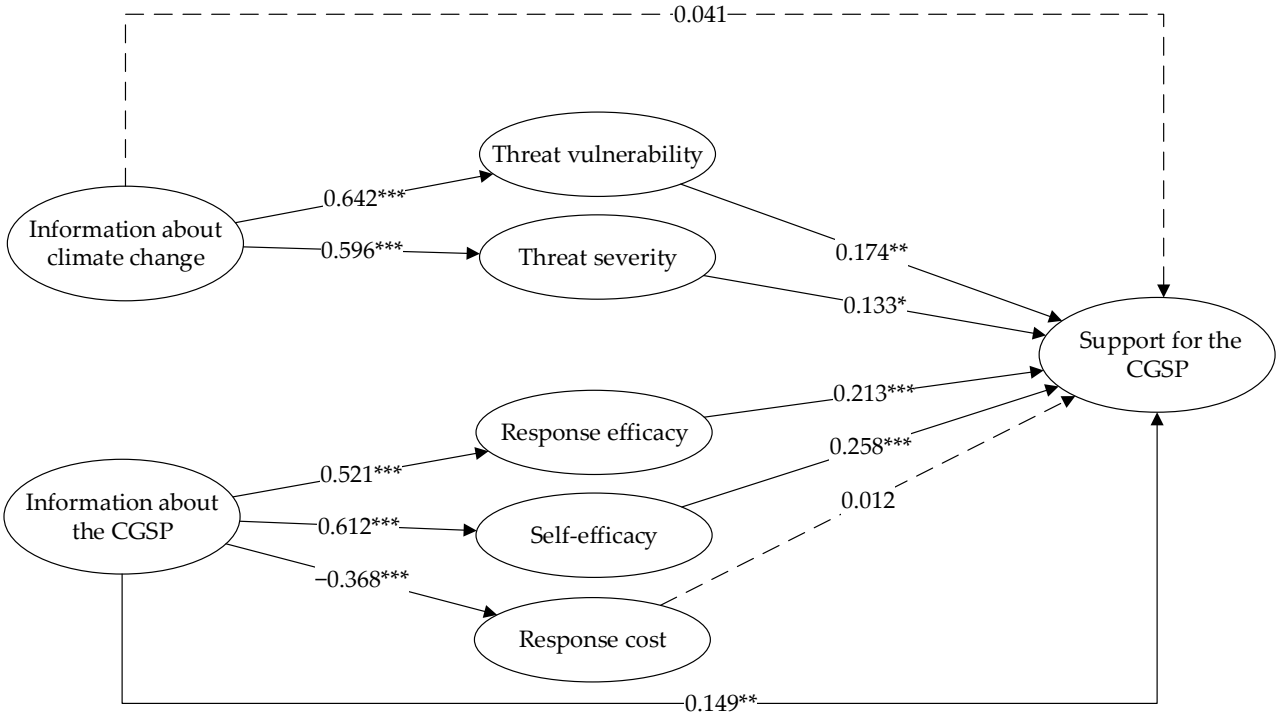


Figure 2. Results of the proposed model (* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$).

Table 6. Summary of the results of testing our hypotheses.

Hypotheses	Standard Estimate	T-Value	Confidence Interval		*p*-Value	Supported
			2.5%	97.5%		
H1a: IACC → TV	0.642 ***	15.050	0.550	0.718	0.000	Yes
H1b: IACC → TS	0.596 ***	12.816	0.496	0.679	0.000	Yes
H2a: IACGSP → RE	0.521 ***	10.805	0.419	0.609	0.000	Yes
H2b: IACGSP → SE	0.612 ***	14.470	0.524	0.688	0.000	Yes
H2c: IACGSP → RC	−0.368 ***	6.346	0.252	0.481	0.000	Yes
H3a: TV → SCGSP	0.174 **	2.893	0.061	0.295	0.004	Yes
H3b: TS → SCGSP	0.133 *	2.582	0.032	0.234	0.010	Yes
H3c: RE → SCGSP	0.213 ***	4.595	0.118	0.301	0.000	Yes
H3d: SE → SCGSP	0.258 ***	4.896	0.154	0.361	0.000	Yes
H3e: RC → SCGSP	0.012	0.358	−0.054	0.076	0.721	No
H10: IACC → SCGSP	0.041	0.837	−0.061	0.078	0.403	No
H11: IACGSP → SCGSP	0.149 **	2.921	0.095	0.224	0.004	Yes
Mediating effects						
IACC → TV → SCGSP	0.112 **	2.908	0.040	0.190	0.004	Yes
IACC → TS → SCGSP	0.079 **	2.574	0.020	0.141	0.010	Yes
IACGSP → RE → SCGSP	0.111 ***	4.166	0.058	0.163	0.000	Yes
IACGSP → SE → SCGSP	0.158 ***	4.676	0.091	0.224	0.000	Yes
IACGSP → RC → SCGSP	−0.004	0.349	−0.019	0.030	0.727	No
Control variables						
Gender → SCGSP	0.005	1.543	−0.009	0.068	0.833	No
Age → SCGSP	0.032	0.835	−0.040	0.102	0.136	No
Educational level → SCGSP	0.019	0.604	−0.027	0.058	0.546	No
Monthly income → SCGSP	0.042	0.493	−0.061	0.115	0.655	No

Notes: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

5. Discussions

5.1. The Effects of Information on Threat and Coping Appraisal

Our findings show that IACC positively affects the two components of the threat appraisal process. Specifically, IACC positively influences TV. This finding resonates with

those of previous studies, suggesting that information is vital in the public's cognitive process and necessary for one's assessment of vulnerability [47]. Also, IACC exerts a positive influence on TS. This implies that increasing the availability and accessibility of information about climate change would strengthen individuals' perceptions of environmental risks [31,69,70,77]. Uniquely, this study found that IACC has a more significant impact on TV than TS, which is novel in the literature. This means that the provision of abundant IACC, in addition to strengthening the public's awareness of the severity of climate change, would exert a more significant impact on reducing the public's optimistic assumptions and psychological distance in which they believe the negative consequences of climate change are far away from them. As a consequence, the public's perceptions that they are susceptible to climate change would be strengthened and their intention to take action to minimize threats would also be aroused.

Moreover, the findings show that IACGSP affects all three components of the coping appraisal process. The significant correlation between information about a certain policy and RE has also been validated by previous studies conducted on residents' pro-environmental behaviors [81,83,84] and public support for environmental policies [5,79,86]. This indicates that information about the CGSP will help the public understand the effectiveness of engaging in the CGSP to reduce carbon emissions. In addition, IACGSP also positively influences SE, which was consistent with the results of Lin and Yang [24], who claimed that the public's access to information about personal carbon reduction policies guides them to form more positive judgements about their ability to adopt equivalent pro-environmental behaviors. Furthermore, IACGSP is negatively associated with RC. This conclusion corroborates the findings of Cismaru et al. [56], indicating that information about countermeasures designed to cope with climate change is an indispensable determinant for RC in stimulating residents' actions in regards to climate change.

5.2. The Effects of Threat and Coping Appraisal on Public Support for the CGSP

Among the two components of threat appraisal in the PMT, TV and TS were both validated as significant predictors of public support for the CGSP. The results echo previous studies on people's pro-environmental behaviors [45,53,55,84,88] and public support for environmental policies [17,52,66,89]. Therefore, if the public perceives that climate change is alarming and they are sensitive to its repercussions after a psychological evaluation, they will be more inclined to support the CGSP. Moreover, the impact of TV on public support is larger than that of TS. This conclusion contradicts some previous findings suggesting that the impact of TV on residents' pro-environmental behavior is larger than that of TV [87,93]. One reason for these alternative findings may be that people view their exposure to the risks of climate change as more important in their decision to support the CGSP.

With regard to the components of coping appraisal in the PMT, the impact of RE on public support for the CGSP was validated. This finding is an agreement with the original PMT hypothesis and coincides with previous studies on residents' pro-environmental behaviors [50,54,87,93] and public support for environmental policies [52,67,94]. Also, SE is a potent driver for public support for the CGSP. This finding corroborates previous studies conducted on residents' pro-environmental behaviors [84,95,96] and public support for environmental policies [97,98]. This implies that if the public thinks that they have the necessary skills to complete the operations accompanied by the CGSP and can easily understand the rules, then they will be willing to support the CGSP.

Unexpectedly, the impact of RC on public support for the CGSP was not significant. This conclusion contradicts the findings of most previous studies [27,99], which claimed that RC is a major barrier for residents to participate in environmentally friendly behaviors or support environmental policies. However, this finding resonates with the results of Tan et al. [20], who declared that implementation cost is not a significant predictor for residents' participation in a voluntary carbon-trading scheme. The reasons for these contradictory observations may be that participating in or supporting the CGSP by adopting certain behaviors is simple and does not come with high costs [23,35]. Additionally, the CGSP

not only provides carbon currency for the public to change for value-added services, like product vouchers and membership services, but also offers non-monetary incentives such as carbon neutrality certification [20,24,25]. These incentives may offset the costs incurred when the public chooses to support the CGSP. As a result, RC would not be a factor that prevents the public from supporting the CGSP.

Moreover, the current study affirmed that the impact of coping appraisal on public support for the CGSP is larger than that of risk appraisal. This finding resonates with the conclusion of most prior studies, which claimed that high perceptions of the risk of climate change may not necessarily translate into actual behaviors if the public perceives that their actions are ineffective in coping with environmental problems [44,52,62,64]. This implies that when the public is confronted with the threat of climate change, they are more concerned with the competence of the CGSP and their ability to properly take corresponding actions. Notably, SE is the foremost predictor of public support for the CGSP, which is commensurate with most previous studies [91]. This implies that the public's assessment of their capacity to do the desired tasks is their major concern regarding their support of the CGSP.

5.3. Mediating Effects of Threat and Coping Appraisal

The results show that IACC did not directly affect public support for the CGSP. This finding contradicts those of previous studies [65,73–76]. However, the current study found that threat appraisal functions as a pivotal mediator in the information–behavior gap, which echoes prior studies affirming the existence of an information–behavior gap in residents' engagement in pro-environmental behaviors [59,68,69,80] and the public in regards to environmental policies [16]. This indicates that while the provision of information about climate change is vital, it is insufficient to convince the public to support the CGSP.

Moreover, the findings show that IACGSP directly influences public support for the CGSP, which corroborates the findings of Authelet et al. [85], which declared that households' information about the incentive-based conservation program's functionality is a crucial predictor of their participation. This finding implies that for the CGSP to function effectively, information that depicts the roles of the public in this endeavor, the actions necessary for tackling the threat, and the actions' benefits are necessary [2,86,100]. Uniquely, this study validates that the public's coping appraisal process works as a pivotal mediator between IACGSP and PSCGSP. This finding indicates that sufficient information about the CGSP would enable the public to more accurately assess their efficacy beliefs to perform corresponding actions, thereby showing a higher level of support for the CGSP.

6. Conclusions, Implications, and Limitations

6.1. Conclusions

This study investigates public support for the CGSP by developing a new theoretical framework that incorporates the PMT and IDM. The proposed model is empirically tested utilizing the PLS-SEM method on 372 respondents in China, and the following crucial findings are recorded. First, our findings confirm that the proposed model has moderate interpretability for public support for the CGSP. Threat vulnerability, threat severity, response efficacy, and self-efficacy all positively affect public support for the CGSP. Information about climate change indirectly influences public support for the CGSP through threat vulnerability and threat severity. Information about the CGSP not only directly affects public support for the CGSP but also indirectly affects public support for the CGSP through response efficacy and self-efficacy. These conclusions may better equip policymakers in developing feasible strategies for the smooth implementation of the CGSP.

6.2. Theoretical Contribution

This study has several theoretical contributions. First, this study contributes to the emerging literature on the CGSP by providing a holistic theoretical framework to unveil the determinants of public support for the CGSP. Due to the novel feature of the CGSP,

prior studies mainly focused on the CGSP's operational mechanism [21,35] and the development of an associated carbon emission reduction calculation methodology [20,23,36]. Public opinions on and inclinations toward the CGSP and their determinants are rarely considered [10,24,25]. This study clarifies how information and threat and coping appraisal affect public support for the CGSP, thereby enriching previous research on the CGSP.

Second, the current study expands the PMT's applicability to the context of the CGSP and contributes to the field of public support for environmental policies. Although previous studies have demonstrated the suitability of the PMT in predicting public support for other environmental policies, such as electric vehicle policies [17], climate policies [52], and renewable energy policies [66], no prior studies have applied the PMT to investigate public support for the CGSP, a novel policy designed to mitigate carbon emissions. In addition, the current study contributes to research on public support for environmental policies by constructing a novel theoretical framework that incorporates the PMT and IDM. These findings highlighted the importance of the incorporation of the PMT and IDM, as the proposed theoretical framework has more explanatory power (61.5%) as compared to those of studies only utilizing the PMT [64,87]. Consequently, the current study can also serve as a reference for investigations into public support for other environmental policies.

Third, the current study investigated the influencing mechanism of information on public support for the CGSP, answering the call for investigations into the information–action gap in environment research [16,68,69,77,78]. Nonetheless, this study makes a novel contribution by dividing the information construct into two dimensions (i.e., IACC and IACGSP) and revealing their different roles in stimulating public support for the CGSP. IACC does not directly affect public support for the CGSP but influences public support for the CGSP through TV and TS. IACGSP not only directly affects public support for the CGSP but also indirectly affects public support for the CGSP through RE and SE. These findings contribute to our understanding of the influencing mechanism of information on climate action.

6.3. Policy Implications

This study also has some implications that may stimulate public support for the CGSP. First, our findings indicate that effective information for increasing public support for the CGSP should be multi-dimensional, as it is necessary to not only provide the public information about climate change but also to provide information about the countermeasures contained in the CGSP that can eradicate or reduce the risks linked to climate change. Therefore, in addition to previous studies highlighting tailored information for the target audience [2,33,56,72], assuring the provision of information regarding both climate change and the CGSP is more important. Therefore, policymakers should pay special attention to enriching the dimensions of information, so that the public can acquire wide-ranging information, enabling them to properly engage in the CGSP. One example could be providing meteorological statistics and charts on climate change trends to show the detrimental consequences of climate change on daily life and highlighting the detailed procedure for participation in the CGSP and its tangible environmental benefits.

Second, the two components of threat appraisal in the PMT, i.e., TV and TS, are significant predictors of public support for the CGSP. Thus, it is essential for policymakers to implement suitable tactics to drive the public's threat appraisal. For instance, the intensity of negative consequences of climate change caused by individuals' carbon emissions should be reinforced through government guidance on a regular basis [10,17]. Also, consensus beliefs about people's susceptibility to climate change should be cultivated through duly explanations of the indiscriminate risks of climate change for human beings in the media [5,72]. One example could be the publicizing of reports from scientific committees and advisory groups on new media platforms such as TikTok and Kwai to popularize people's susceptibility to climate change.

Third, given the significant role of RE and SE in the coping appraisal process in stimulating public support for the CGSP, heightening the public's efficacy beliefs regarding

the CGSP is central to intervention strategies. Therefore, policymakers should increase the public's sense of response efficacy by highlighting that every individual can contribute to mitigating climate change [48]. Statistics, calculators, and visualized carbon emission reductions may be effective ways to lift the public's beliefs that their actions to support the CGSP counts toward China's carbon emission goals. Additionally, the public's self-efficacy should also be strengthened by some targeted educational programs and lectures [24,45], as these measures would equip the public with more skills and serve as guidance or instructions for the public to participate in the CGSP.

6.4. Limitations and Future Work

The current study acquires limitations that could indicate directions for further investigation. First, as self-reported surveys may yield skewed answers, future researchers might conduct interviews or behavioral experiments for related investigations. Second, the data were collected in China; however, pollution levels, policy conditions, and public preferences in different areas and countries may be different. Therefore, future researchers could conduct surveys in other places or nations to investigate behavioral variations. Finally, as the current study's focus is confined to public support for the CGSP, the results and implications are unlikely to be generalizable to other carbon policies. Considering that public support for different types of policies may be different, future studies could concentrate on acquiring empirical data or expanding the current model for generalizability to explore public support for other kinds of policies.

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References

1. Moon, W.K.; Kahlor, L.A.; Olson, H.C. Understanding public support for carbon capture and storage policy: The roles of social capital, stakeholder perceptions, and perceived risk/benefit of technology. *Energy Policy* **2020**, *139*, 111312. [CrossRef]
2. Hu, Q.S.; Becken, S.; He, X.R. Climate risk perception and adaptation of tourism sector in China. *J. Destin. Mark. Manag.* **2022**, *23*, 100675. [CrossRef]
3. Odland, S.; Rhodes, E.; Gorbett, M.; Pardy, A. What policies do homeowners prefer for building decarbonization and why? An exploration of climate policy support in Canada. *Energy Policy* **2023**, *173*, 113368. [CrossRef]
4. Wiseman, J.; Edwards, T.; Luckins, K. Post carbon pathways: A meta-analysis of 18 large-scale post carbon economy transition strategies. *Environ. Innov. Soc. Transit.* **2013**, *8*, 76–93. [CrossRef]
5. Tschotschel, R.; Schuck, A.; Schwinges, A.; Wonneberger, A. Climate change policy support, intended behaviour change, and their drivers largely unaffected by consensus messages in Germany. *J. Environ. Psychol.* **2021**, *76*, 101655. [CrossRef]
6. Li, F.L.; He, K.; Zhu, R.; Zhang, J.B.; Gao, M. Rural low-carbon energy development in the information age: Can internet access drive the farmer to participate in personal carbon trading schemes related to bioenergy? *Sustain. Dev.* **2022**, *31*, 1417–1432. [CrossRef]
7. Drews, S.; van den Bergh, J.C.J.M. What explains public support for climate policies? A review of empirical and experimental studies. *Clim. Policy* **2016**, *16*, 855–876. [CrossRef]
8. Song, X.; Shen, M.; Lu, Y.; Shen, L.; Zhang, H. How to effectively guide carbon reduction behavior of building owners under emission trading scheme? An evolutionary game-based study. *Environ. Impact Assess. Rev.* **2021**, *90*, 106624. [CrossRef]
9. Gao, L.; He, H.N.; Wang, S.Y.; Li, J. What drives resident acceptance of personal carbon trading policy in China? *Environmental Geochem. Health* **2022**, *44*, 3007–3020. [CrossRef] [PubMed]

10. Gao, L.; Jiang, J.J.; He, H.N.; Zhou, Q.; Wang, S.Y.; Li, J. Uncertainty or trust? Political trust, perceived uncertainty and public acceptance of personal carbon trading policy. *Environ. Geochem. Health.* **2022**, *44*, 3157–3171. [CrossRef] [PubMed]
11. Bristow, A.L.; Wardman, M.; Zanni, A.M.; Chintakayala, P.K. Public acceptability of personal carbon trading and carbon tax. *Ecol. Econ.* **2010**, *69*, 1824–1837. [CrossRef]
12. Dreyer, S.J.; Walker, J. Acceptance and Support of the Australian Carbon Policy. *Soc. Justice Res.* **2013**, *26*, 343–362. [CrossRef]
13. Rhodes, E.; Axsen, J.; Jaccard, M. Exploring citizen support for different types of climate policy. *Ecol. Econ.* **2017**, *137*, 56–69. [CrossRef]
14. Chen, X.; Lin, B. Towards carbon neutrality by implementing carbon emissions trading scheme: Policy evaluation in China. *Energy Policy* **2021**, *157*, 112510. [CrossRef]
15. Hasanaj, V.; Stadelmann-Steffen, I. Is the problem or the solution riskier? Predictors of carbon tax policy support. *Environ. Res. Commun.* **2022**, *4*, 105001. [CrossRef]
16. Tobler, C.; Visschers, V.H.M.; Siegrist, M. Addressing climate change: Determinants of consumers' willingness to act and to support policy measures. *J. Environ. Psychol.* **2012**, *32*, 197–207. [CrossRef]
17. Bockarjova, M.; Steg, L. Can protection motivation theory predict pro-environmental behavior? Explaining the adoption of electric vehicles in The Netherlands. *Glob. Environ. Change* **2014**, *28*, 276–288. [CrossRef]
18. Nilsson, A.; Hansla, A.; Heiling, J.M.; Bergstad, C.J.; Martinsson, J. Public acceptability towards environmental policy measures: Value-matching appeals. *Environ. Sci. Policy* **2016**, *61*, 176–184. [CrossRef]
19. Ru, X.; Qin, H.; Wang, S. Young people's behaviour intentions towards reducing PM2.5 in China: Extending the theory of planned behaviour. *Resour. Conserv. Recycl.* **2019**, *141*, 99–108. [CrossRef]
20. Tan, X.P.; Wang, X.Y.; Zaidi, S.H.A. What drives public willingness to participate in the voluntary personal carbon-trading scheme? A case study of Guangzhou Pilot, China. *Ecol. Econ.* **2019**, *165*, 106389. [CrossRef]
21. Xiao, Y.H.; Jiang, Y.P.; Du, M.; Gan, S.J.; Tan, Z.T.; Tan, X.L.; Zhang, M.; Wu, X.B. A new carbon emission reduction mechanism: Carbon Generalized System of Preferences (CGSP). *Environ. Sci. Pollut. Res.* **2021**, *28*, 1267–1274. [CrossRef]
22. Yang, H.C.; Cheng, Y.L. Knowledge graph analysis of progress in carbon generalized systems of preference research. *Adv. Appl. Math.* **2022**, *11*, 62–74. [CrossRef]
23. Yu, W.; Wang, T.; Xiao, Y.; Chen, J.; Yan, X. A carbon emission measurement method for individual travel based on transportation big data: The case of Nanjing metro. *Int. J. Environ. Res. Public Health* **2020**, *17*, 5957. [CrossRef] [PubMed]
24. Lin, B.Q.; Yang, M.Q. Choosing the right policy: Factors influencing the preferences of consumption-side personal carbon reduction policies. *J. Environ. Manag.* **2023**, *326*, 116706. [CrossRef]
25. Si, H.; Li, N.; Cheng, L.; Bao, Z. Understanding the public's willingness to participate in the carbon generalized system of preferences (CGSP): An innovative mechanism to drive low-carbon behavior in China. *Sust. Prod. Consum.* **2023**, *38*, 1–12. [CrossRef]
26. China Carbon Neutrality Forum. Personal carbon account research design. 2022. Available online: https://www.sgpjbg.com/baogao/107794.html (accessed on 20 December 2023).
27. De Groot, J.I.M.; Schuitema, G. How to make the unpopular popular? Policy characteristics, social norms and the acceptability of environmental policies. *Environ. Sci. Policy* **2012**, *19–20*, 100–107. [CrossRef]
28. Harring, N.; Jagers, S.C. Why do people accept environmental policies? The prospects of higher education and changes in norms, beliefs and policy preferences. *Environ. Educ. Res.* **2018**, *24*, 791–806. [CrossRef]
29. Jain, N.K.; Kaushik, K.; Choudhary, P. Sustainable perspectives on transportation: Public perception towards odd-even restrictive driving policy in Delhi, India. *Transp. Policy* **2021**, *106*, 99–108. [CrossRef]
30. Maestre-Andres, S.; Drews, S.; Savin, I.; van der Bergh, J. Carbon tax acceptability with information provision and mixed revenue uses. *Nat. Commun.* **2021**, *12*, 7017. [CrossRef]
31. Dietz, T.; Dan, A.; Shwom, R. Support for climate change policy: Social psychological and social structural influences. *Rural Sociol.* **2007**, *72*, 185–214. [CrossRef]
32. Rhodes, E.; Axsen, J.; Jaccard, M. Does effective climate policy require well-informed citizen support? *Glob. Environ. Change* **2014**, *29*, 92–104. [CrossRef]
33. Wan, C.; Shen, G.Q.; Choi, S. Understanding public support for recycling policy: To unveil the political side of influence and implications. *Environ. Sci. Policy* **2018**, *82*, 30–43. [CrossRef]
34. Yeganeh, A.J.; McCoy, A.P.; Schenk, T. Determinants of climate change policy adoption: A meta-analysis. *Urban Clim.* **2020**, *31*, 100547. [CrossRef]
35. Li, W.; Ceng, X.; Liang, X.; Bian, Y.; Xu, W.; Ang, Y. Research on carbon emission reduction calculation of urban public bicycle system base upon generalised carbon trading. *China Popul. Resour. Environ.* **2016**, *26*, 103–107.
36. Huang, Y.; Guo, H.; Xie, P.; Liao, C.; Zhao, D. Study on carbon emission reduction calculation of subway travel-take Guangzhou as an example. *Clim. Change Res.* **2017**, *13*, 284–291.
37. Wan, C.; Shen, G.Q.; Yu, A. The role of perceived effectiveness of policy measures in predicting recycling behavior in Hong Kong. *Resour. Conser. Recycl.* **2014**, *83*, 141–151. [CrossRef]
38. Huber, R.A.; Wicki, M.L.; Bernauer, T. Public support for environmental policy depends on beliefs concerning effectiveness, intrusiveness, and fairness. *Environ. Politics* **2019**, *29*, 649–673. [CrossRef]
39. Burstein, P. The impact of public opinion on public policy: A review and an agenda. *Political Res. Q.* **2003**, *56*, 29–40. [CrossRef]

40. Steg, L.; Dreijerink, L.; Abrahamse, W. Factors influencing the acceptability of energy policies: A test of VBN theory. *J. Environ. Psychol.* **2005**, *25*, 415–425. [CrossRef]
41. Fobissie, E.N. The role of environmental values and political ideology on public support for renewable energy policy in Ottawa, Canada. *Energy Policy* **2019**, *134*, 110918. [CrossRef]
42. Rogers, R.W. A protection motivation theory of fear appeals and attitude change. *J. Psychol.* **1975**, *91*, 93e114. [CrossRef]
43. Rippetoe, P.A.; Rogers, R.W. Effects of components of protection motivation theory on adaptive and maladaptive coping with a health threat. *J. Personal. Soc. Psychol.* **1987**, *52*, 596–604. [CrossRef]
44. Floyd, D.L.; Prentice-Dunn, S.; Rogers, R.W. A meta-analysis of research on protection motivation theory. *J. Appl. Soc. Psychol.* **2000**, *30*, 407–429. [CrossRef]
45. Badsar, M.; Moghm, M.; Ghasemi, M. Analysis of factors influencing farmers' sustainable environmental behavior in agriculture activities: Integration of the planned behavior and the protection motivation theories. *Environ. Dev. Sust.* **2022**, *25*, 9903–9934. [CrossRef]
46. Kothe, E.J.; Ling, M.; North, M.; Klas, A.; Mullan, B.A.; Novoradovskaya, L. Protection motivation theory and pro-environmental behaviour: A systematic mapping review. *Aust. J. Psychol.* **2019**, *71*, 411–432. [CrossRef]
47. Xue, M.T.; Zhao, Y.D.; Zhang, Z.H.; Zhang, B. Behavioural determinants of an individual's intention to adapt to climate change: Both internal and external perspectives. *Environ. Impact Assess. Rev.* **2021**, *91*, 106672. [CrossRef]
48. Wang, W.S.; Mo, T.T.; Wang, Y.C. Better self and better us: Exploring the individual and collective motivations for China's Generation Z consumers to reduce plastic pollution. *Resour. Conserv. Recycl.* **2022**, *179*, 106111. [CrossRef]
49. Milne, S.; Sheeran, P.; Orbell, S. Prediction and intervention in health-related behavior: A meta-analytic review of protection motivation theory. *J. Appl. Soc. Psychol.* **2000**, *30*, 106–143. [CrossRef]
50. Wang, Y.D.; Liang, J.P.; Yang, J.; Ma, X.X.; Li, X.Q.; Wu, J.; Yang, G.H.; Ren, G.X.; Feng, Y.Z. Analysis of the environmental behavior of farmers for non-point source pollution control and management: An integration of the theory of planned behavior and the protection motivation theory. *J. Environ. Manag.* **2019**, *237*, 15–23. [CrossRef] [PubMed]
51. Ruan, W.J.; Kang, S.H.; Song, H. Applying protection motivation theory to understand international tourists' behavioural intentions under the threat of air pollution: A case of Beijing, China. *Curr. Issues Tour.* **2020**, *23*, 2027–2041. [CrossRef]
52. Lam, S.P. Predicting support of climate policies by using a protection motivation model. *Clim. Policy* **2015**, *15*, 321–338. [CrossRef]
53. Chen, M.F. Moral extension of the protection motivation theory model to predict climate change mitigation behavioral intentions in Taiwan. *Environ. Sci. Pollut. Research.* **2020**, *27*, 13714–13725. [CrossRef]
54. Villamor, G.B.; Vakelin, S.J.; Dunningham, A.; Clinton, P.W. Climate change adaptation behaviour of forest growers in New Zealand: An application of protection motivation theory. *Clim. Change* **2023**, *176*, 3. [CrossRef]
55. Grothmann, T.; Patt, A. Adaptive capacity and human cognition: The process of individual adaptation to climate change. *Glob. Environ. Change* **2005**, *15*, 199–213. [CrossRef]
56. Cismaru, M.; Cismaru, R.; Ono, T.; Nelson, K. "Act on climate change": An application of protection motivation theory. *Soc. Mark. Q.* **2011**, *17*, 62–84. [CrossRef]
57. Burgess, J.; Harrison, C.M.; Filius, P. Environmental communication and the cultural politics of environmental citizenship. *Environ. Plan. A-Econ. Space* **1998**, *30*, 1445–1460. [CrossRef]
58. McNie, E.C. Reconciling the supply of scientific information with user demands: An analysis of the problem and review of the literature. *Environ. Sci. Policy* **2007**, *10*, 17–38. [CrossRef]
59. Abunyewah, M.; Gajendran, T.; Maund, K.; Okyere, S.A. Strengthening the information deficit model for disaster preparedness: Mediating and moderating effects of community participation. *Int. J. Disaster Risk Reduct.* **2020**, *46*, 101492. [CrossRef]
60. Rogers, R.W. Cognitive and physiological processes in fear appeals and attitude change: A revised theory of protection motivation. In *Social Psychology. A sourcebook*; Cacioppo, J.R., Petty, R.E., Eds.; Guilford: New York, NY, USA, 1983; pp. 153–176.
61. Rogers, R.W.; Prentice-Dunn, S. Protection motivation theory. In *Handbook of Health Behavior Research 1: Personal and Social Determinants*; Plenum Press: New York, NY, USA, 1997; pp. 113–132.
62. Gebrehiwot, T.; van der Veen, A. Farmers'drought experience, risk perceptions, and behavioural intentions for adaptation: Evidence from Ethiopia. *Clim. Dev.* **2021**, *13*, 493–502. [CrossRef]
63. Wang, J.; Liu-Lastres, B.J.; Ritchie, B.W.; Mills, D.J. Travellers' self-protections against health risks: An application of the full protection motivation theory. *Ann. Tour. Res.* **2019**, *78*, 102743. [CrossRef]
64. Rainear, A.M.; Christensen, J.L. Examining pre-existing environmental beliefs: Using a PSA to investigate the role of self-efficacy and response efficacy on behavioral intentions. *Commun. Stud.* **2022**, *73*, 151–170. [CrossRef]
65. Tchetchik, A.; Kaplan, S.; Blass, V. Recycling and consumption reduction following the COVID-19 lockdown: The effect of threat and coping appraisal, past behavior and information. *Resour. Conserv. Recycl.* **2021**, *167*, 105370. [CrossRef]
66. Olson-Hazboun, S.K.; Howe, P.D.; Leiserowitz, A. The influence of extractive activities on public support for renewable energy policy. *Energy Policy* **2018**, *123*, 117–126. [CrossRef]
67. Tasantab, J.C.; Gajendran, T.; Maund, K. Expanding protection motivation theory: The role of coping experience in flood risk adaptation intentions in informal settlements. *Int. J. Disaster Risk Reduct.* **2022**, *76*, 103020. [CrossRef]
68. Lemos, M.C.; Krichhoff, C.J.; Ramprasad, V. Narrowing the climate information usability gap. *Nat. Clim. Change* **2012**, *2*, 789–794. [CrossRef]

69. Dong, Y.; Hu, S.; Zhu, J. From source credibility to risk perception: How and when climate information matters to action. *Resour. Conserv. Recycl.* **2018**, *136*, 410–417. [CrossRef]
70. Stoutenborough, J.W.; Vedlitz, A. The effect of perceived and assessed knowledge of climate change on public policy concerns: An empirical comparison. *Environ. Sci. Policy* **2014**, *37*, 23–33. [CrossRef]
71. Shi, J.; Visschers, V.H.M.; Siegrist, M. Public perception of climate change: The importance of knowledge and cultural worldviews. *Risk Anal.* **2015**, *35*, 2183–2201. [CrossRef]
72. Kronrod, A.; Tchetchik, A.; Grinstein, A.; Turgeman, L.; Blass, V. Promoting new pro-environmental behaviors: The effect of combining encouraging and discouraging messages. *J. Environ. Psychol.* **2023**, *86*, 101945. [CrossRef]
73. Bidwell, D. The effects of information on public attitudes toward renewable energy. *Environ. Behav.* **2016**, *48*, 743–768. [CrossRef]
74. Lim-Wavde, K.; Kauffman, R.J.; Dawson, G.S. Household informedness and policy analytics for the collection and recycling of household hazardous waste in California. *Resour. Conserv. Recycl.* **2017**, *120*, 88–107. [CrossRef]
75. Bergquist, P.; Marlon, J.R.; Goldberg, M.H.; Gustafson, A.; Rosenthal, S.A.; Leiserowitz, A. Information about the human causes of global warming influences causal attribution, concern, and policy support related to global warming. *Think Reason* **2022**, *28*, 465–486. [CrossRef]
76. Wei, J.; Zhang, L.; Yang, R.; Song, M. A new perspective to promote sustainable low-carbon consumption: The influence of informational incentive and social influence. *J. Environ. Manag.* **2022**, *327*, 116848. [CrossRef]
77. Kellstedt, P.M.; Zahran, S.; Vedlitz, A. Personal efficacy, the information environment, and attitudes toward global warming and climate change in the United States. *Risk Anal.* **2008**, *28*, 113–126. [CrossRef] [PubMed]
78. Yilmaz, V.; Gulec, P.; Ari, E. Impact of climate change information of university students in Turkey on responsibility and environmental behavior through awareness and perceived risk. *Environ. Dev. Sustain.* **2022**, *25*, 7281–7297. [CrossRef]
79. Ehret, P.J.; Sparks, A.C.; Sherman, D.K. Support for environmental protection: An integration of ideological-consistency and information-deficit models. *Environ. Politics* **2017**, *26*, 253–277. [CrossRef]
80. Di Falco, S.; Sharma-Khushal, S. Cognitive drivers, and the effect of information on climate change adaptive behaviour in Fiji Islands. *Environ. Sci. Policy* **2019**, *92*, 245–254. [CrossRef]
81. Bijani, M.; Mohammadi-Mehr, S.; Shiri, N. Towards rural women's pro-environmental behaviors: Application of protection motivation theory. *Glob. Ecol. Conserv.* **2022**, *39*, e02303. [CrossRef]
82. Wibeck, V. Enhancing learning, communication and public engagement about climate change—Some lessons from recent literature. *Environ. Educ. Res.* **2014**, *20*, 287–411. [CrossRef]
83. Gumasing, M.J.J.; Prasetyo, Y.T.; Ong, A.K.S.; Nadlifatin, R. Determination of factors affecting the response efficacy of Filipinos under Typhoon Conson 2021 (Jolina): An extended protection motivation theory approach. *Int. J. Disaster Risk Reduct.* **2022**, *70*, 102759. [CrossRef]
84. Zobeidi, T.; Yaghoubi, J.; Yazdanpanah, M. Farmers' incremental adaptation to water scarcity: An application of the model of private proactive adaptation to climate change (MPPACC). *Agric. Water Manag.* **2022**, *264*, 107528. [CrossRef]
85. Authelet, M.; Subervie, J.; Meyfroidt, P.; Asquith, N.; Ezzine-de-Blas, D. Economic, pro-social and pro-environmental factors influencing participation in an incentive-based conservation program in Bolivia. *World Dev.* **2021**, *145*, 105487. [CrossRef]
86. Tao, Y.J.; Duan, M.S.; Deng, Z. Using an extended theory of planned behaviour to explain willingness towards voluntary carbon offsetting among Chinese consumers. *Ecol. Econ.* **2021**, *185*, 107068. [CrossRef]
87. Keshavarz, M.; Karami, E. Farmers' pro-environmental behavior under drought: Application of protection motivation theory. *J. Arid Environ.* **2016**, *127*, 128–136. [CrossRef]
88. Ghazali, S.; Azadi, H.; Kurban, A.; Ajtai, N.; Pietrzykowski, M.; Witlox, F. Determinants of farmers' adaptation decisions under changing climate: The case of Fars province in Iran. *Clim. Chang.* **2021**, *166*, 6. [CrossRef]
89. Stoutenborough, J.W.; Sturgess, S.G.; Vedlitz, A. Knowledge, risk, and policy support: Public perceptions of nuclear power. *Energy Policy* **2013**, *62*, 176–184. [CrossRef]
90. Defiyan, F.; Yazdanpanah, M.; Forouzani, M.; Yaghoubi, J. Farmers' adaptation to drought risk through farm-level decisions: The case of farmers in Dehloran county, Southwest of Iran. *Clim. Dev.* **2020**, *13*, 152–163. [CrossRef]
91. Savari, M.; Naghineiranvand, F.; Asadi, Z. Modeling environmentally responsible behaviors among rural women in the forested regions in Iran. *Glob. Ecol. Conserv.* **2022**, *35*, e02102. [CrossRef]
92. Van Valkengoed, A.M.; Steg, L. Meta-analyses of factors motivating climate change adaptation behaviour. *Nature Clim. Chang.* **2019**, *9*, 158–163. [CrossRef]
93. Kim, S.; Jeong, S.H.; Hwang, Y. Predictors of pro-environmental behaviors of American and Korean students: The application of the theory of reasoned action and protection motivation theory. *Sci. Commun.* **2013**, *35*, 168–188. [CrossRef]
94. Houser, M.; Gazley, B.; Reynolds, H.; Browning, E.G.; Sandweiss, E.; Shanahan, J. Public support for local adaptation policy: The role of social-psychological factors, perceived climatic stimuli, and social structural characteristics. *Glob. Environ. Change* **2022**, *72*, 102424. [CrossRef]
95. Chen, A.H.; Lu, Y.B. Protective behavior in ride-sharing through the lens of protection motivation theory and usage situation theory. *Int. J. Inf. Manag.* **2021**, *61*, 102402. [CrossRef]
96. Horng, J.S.; Hu, M.L.M.; Teng, C.C.C.; Lin, L. Energy saving and carbon reduction behaviors in tourism—A perception study of Asian visitors from a protection motivation theory perspective. *Asia Pacific J. Tourism Res.* **2014**, *19*, 721–735. [CrossRef]

97. Geiger, N.; Swim, J.K.; Fraser, J. Creating a climate for change: Interventions, efficacy and public discussion about climate change. *J. Environ. Psychol.* **2017**, *51*, 104–116. [CrossRef]
98. Juan, M.R.; Revilla, M. Support for mitigation and adaptation climate change policies: Effect of five attitudinal factors. *Mitig. Adapt. Strateg. Glob. Change* **2021**, *26*, 28. [CrossRef]
99. Pakmehr, S.; Yazdanpanah, M.; Baradaran, M. How collective efficacy makes a difference in response to water shortage due to climate change in southwest Iran. *Land Use Policy* **2020**, *99*, 104798. [CrossRef]
100. Lorenzoni, I.; Nicholson-Cole, S.; Whitmarsh, L. Barriers perceived to engaging with climate change among the UK public and their policy implications. *Glob. Environ. Change* **2007**, *17*, 445–459. [CrossRef]
101. Menold, N.; Tausch, A. Measurement of latent variables with different rating scales: Testing reliability and measurement equivalence by varying the verbalization and number of categories. *Sociol. Methods Res.* **2016**, *45*, 678–699. [CrossRef]
102. CNNIC (China Internet Network Information Center). The 50th China Statistical Report on Internet Development. 2022. Available online: https://www.cnnic.net.cn/n4/2022/0914/c88-10226.html (accessed on 20 December 2023).
103. National Bureau of Statistics. Statistical Communique of the People's Republic of China on National Economic and Social Development in 2022. 2022. Available online: http://www.stats.gov.cn/tjsj/zxfb/202302/t20230227_1918980.html (accessed on 20 December 2023).
104. Hair, J.F.; Hult, G.T.; Ringle, C.M.; Sarstedt, M. *A Primer on Partial Least Squares Structural Equation Modeling (PLS-SEM)*; Sage: Thousand Oaks, CA, USA, 2022.
105. Sarstedt, M.; Hair, J.F.; Ringle, C.M. "PLS-SEM: Indeed a silver bullet"—Retrospective observations and recent advances. *J. Market. Theory Practice* **2022**, *31*, 261–275. [CrossRef]
106. Hair, J.F.; Risher, J.J.; Sarstedt, M.; Ringle, C.M. When to use and how to report the results of PLS-SEM. *Eur. Bus. Rev.* **2019**, *31*, 2–24. [CrossRef]
107. Ringle, C.M.; Wende, S.; Becker, J.M. *SmartPLS 4*; SmartPLS: Oststeinbek, Germany, 2022.
108. Fornell, C.; Larcker, D.F. Evaluating structural equation models with unobservable variables and measurement error. *J. Mark. Res.* **1981**, *18*, 39–50. [CrossRef]
109. Henseler, J.; Ringle, C.M.; Sarstedt, M. A new criterion for assessing discriminant validity in variance-based structural equation modeling. *J. Mark. Theory Pract.* **2015**, *43*, 115–135. [CrossRef]
110. Podsakoff, P.M.; Organ, D.W. Self-reports in organizational research: Problems and prospects. *J. Manag.* **1986**, *12*, 531–544. [CrossRef]

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Focus Group Discussions on Food Waste: An Empirical Application Providing Insights into Rural and Urban Households in Greece

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Abstract: This paper demonstrates the utility of the focus group discussions (FGDs) methodology in the scientific exploration of food waste. The main objective is to show how FGDs can be designed and implemented by collecting data on household food waste (HFW). The paper provides an empirical application of FGDs to members of urban and rural households in Greece through 10 steps. It is qualitative research that was implemented as a supplement in the framework of a large-scale study on HFW, providing an in-depth interpretation of the statistical results that were arrived at. The research shows that FGDs are an effective data collection methodology that reveals insights into HFW through interactions and complex behaviors. Further, the methodology used gives the opportunity to bring information to the fore. The role of women in relation to food-related responsibilities in the Greek household and the impact of rural experiences on HFW composition constitute two topics under exploration. A detailed understanding of HFW examined through the FGDs methodology enriches the global bibliography, mainly for the case of Greece. In addition, useful information is provided to local and governmental bodies, enabling them to collaborate with academics and experts in food waste management. There is a willingness among household members to raise their awareness of HFW reduction and prevention.

Keywords: factors; household food waste; interviews; qualitative research; rurality

1. Introduction

Food wastage is a complex global phenomenon that entails a variety of social, environmental, and economic issues [1] and occurs at different stages along the food supply chain (FSC) [2]. Globally, one-third of edible food is wasted every year [3], while millions of people in developing countries are undernourished [4]. Food waste is mainly observed at the "public and household consumption" stage [1,5], but differs across countries and local communities—urban and rural. [6,7].

HFW (household food waste) composition in Greece does not differ significantly from other Mediterranean countries [8–10]). The most rejected foods in Greek households are fresh fruits, vegetables [10,11], and cooked-food leftovers, not excluding meat or fish [10]. HFW composition is strictly connected to the available knowledge, formed perceptions, and attitudes formed through food-related household activities, mainly including shopping, cooking, and leftovers management [11–13]. More specifically, people buy and cook more food than they should. In this way, they produce food waste which they are not going to consume in other meals or in feeding animals. Moreover, this situation is further burdened

by the ignorance of food labels content. The most common issue that increases HFW is that people often struggle to interpret the dates on food labels [14].

A plethora of studies have been conducted globally in recent years exploring HFW, the majority of which suggest that specific factors influence HFW composition [15]. The most prominent factors are age, gender, profession, and place of residence [15–18]. Based on the latest literature, older individuals [19], males [20], those who are unemployed or seeking employment [21], as well as rural inhabitants [22] tend to waste less food compared to their younger, female, employed, and urban counterparts. Nevertheless, there is a lack of evidence substantiating these observations [13].

The main objective of the current paper is to advance the understanding of factors influencing HFW, and, thus, to shed light on its causes and consequences. More specifically, this paper concerns supplementary research that was included [23] within a comprehensive empirical study on HFW in Greece. The need to interpret some of the surveys' statistical results induced the research team to organize and implement in-depth interviews. Within this framework, the FGD_S method [24] was used. The selection of this method compelled the research team to expound upon and enrich the global bibliography with detailed insights into the most common quantitative findings (factors) concerning HFW [9,20,21].

This research addresses seven crucial findings regarding HFW composition, providing a clearer insights into them. The following are the key findings presented in detail:

1. Women are the primarily contributors to the composition of HFW. According to the descriptive statistics, 62% of women are responsible for household food purchases and 87% of them for cooking;
2. Individuals who are 26–45 years old are more likely to waste more food than the elderly (65+ years old). Based on the descriptive statistics, 70% of individuals aged 65 and over declared that they never discard food in their households while 65% of individuals aged 18–25 are more likely to compose HFW;
3. Younger people (18–25 years old) are more likely to waste more food than the 26–45 age range The descriptive statistics reveal that 26% of individuals aged 18–25 discard more food than 17% of individuals aged 26–45 who discard less food at the household level;
4. Rural food-related experiences have a positive influence on HFW composition. The two-step cluster analysis shows that household members who have lived in the past in a rural area (75%) and/or come from a rural area (80%) are characterized by socio-ecological awareness of food waste issues;
5. Food labeling dates have a negative influence on HFW composition. The results of the categorical principal components analysis (CPCA) disclose that household members are not used to consuming foods after the "best before date" (median 2.68) or to buying and/or consuming food close to their expiry date (median 1.95);
6. Consumers' attitudes encompass both beneficial and non-harmful food-related habits and behaviors with regard to HFW composition, e.g., to use the FIFO consumption method (first-in-first-out), to reduce overconsumption, etc. The most relevant result with regard to the above attitude is that the CPCA analysis reveals that household members use the FIFO method (median 2.85), eat leftovers in other meals (median 3.97), eat more than they need (median 2.80), and try to discard less food (median 4.50);
7. There are insufficient or erroneous perceptions of environmental issues linked to HFW composition such as food miles and climate change. Based on the CPCA results, household members are not aware of the impact of human activity on nature and climate change as well (median 2.48), and they do not realize that local foods are less harmful to the environment than imported foods (median 2.55).

The current paper presents a first attempt, for the case of Greece, to interpret the most common issues related to HFW composition. The innovation of the paper concerns the application of the FGDs qualitative methodology on food waste issues. A step-by-step FGDs process is presented, providing a better understanding of food waste production by household members. More specifically, the short daily food stories of FGDs participants

are proven to be a vital source of information that explains the composition of food waste in rural and urban households in the study area. Policies and limitations are also included at the end of the paper.

2. Methods

Data for this research were collected from a sample of the Greek population in the municipality of Eordaia, Western Macedonia. Firstly, an empirical study on HFW was conducted through a survey questionnaire, and 279 valid responses were collected. The stratified sampling technique [5] indicated a sample of 193 households from the 1 urban community and 86 households from the 25 rural communities that comprise the study area. The data were collected, encoded, recorded, and analyzed statistically. Data analysis revealed findings on food waste issues but proved insufficient to provide clear evidence on HFW causes and consequences. Therefore, it was deemed essential to conduct supplementary qualitative research in order to identify why and how specific demographics make an impact on HFW composition.

The FGDs methodology [25] was selected, and the necessary data were compiled in 10 steps, which are described below (Figure 1) [26]:

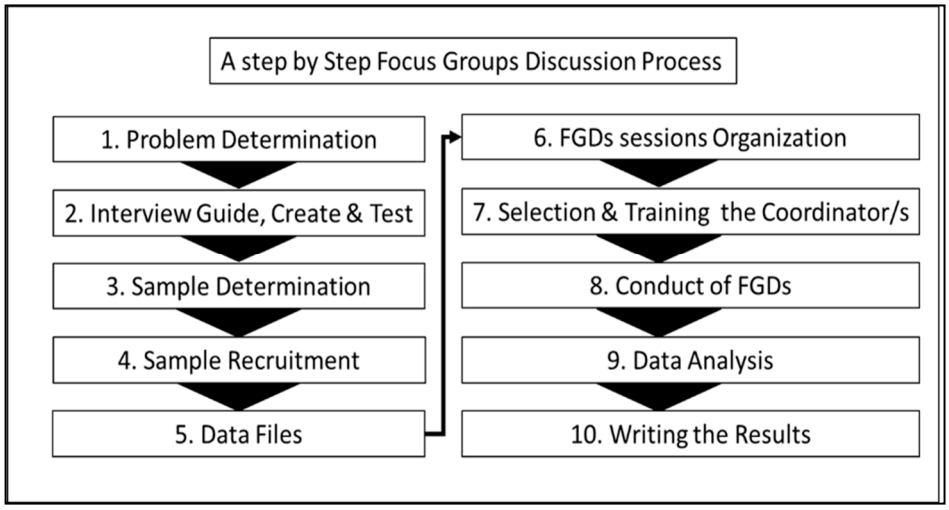


Figure 1. FGD_S methodology, a step-by-step approach to HFW issues.

Step 1—Problem determination: According to the statistical analysis of a large-scale study on HFW, some results with no clear understanding were obtained. In order to provide clear evidence relating to factors, causes, and consequences affecting HFW, the FGDs method was chosen to provide valuable insights.

Step 2—Interview guide, creation, and test: An interview guide of 17 open-ended questions (Appendix A, Table A1) was created based on the statistical results mentioned above (step 1). The interview guide was tested to ensure that all the participants understood the questions, providing the required information. In this manner, the framework for the guide's validity and reliability was established [27].

Step 3—Sample determination: Participants were selected according to the purposive sampling technique [28,29], whereby they met a combination of heterogeneous and homogeneous criteria. The heterogeneity of the sample was attributed to the participants' different genders, ages, educational levels, and residential places—urban or rural. Their homogeneity lay in the fact that all of them were residents of the same municipality. Furthermore, the heterogeneity promotes motivation for discussion, while the homogeneity facilitates the communication among interviewees, thus encouraging them to share their perceptions, ideas, and experiences [30].

Step 4—Sample recruitment: Interviewees participated voluntarily without any recruitment involving monetary incentives. This step is not a prerequisite for implementing

FGDs, as these payments are not a common motivation and are mainly used to increase interview participation [31].

Step 5—Data files: All interviewees, before the session started, received a specially structured folder that included four files:

i. Information sheet which included all the details about the research process, the assurance of their anonymity, as well as contact information.
ii. Answer sheet (Appendix A, Table A2). The interviewees were asked to briefly record their opinions after the discussion of each question. The need to record the answers of the interviewees themselves was created in order to avoid losing answers. The coordinator was simultaneously briefly recording the answers, along with the interactions among the interviewees [32].
iii. Practical advice sheet which included 9 tips (Appendix A, Figure A1) about how to reduce and/or prevent HFW, published by the Food and Agriculture Organization of the United Nations [33].
iv. "Every Food on the Right Shelf" sheet which included information about the proper food storage places on household shelves, in kitchens, and in refrigerators, published by the Academy of Nutrition and Dietetics [34].

Both the third and fourth sheets were given to interviewees at the end of their session as a gift—reminder. The main purpose of this gift was to encourage all interviewees to enhance HFW prevention and/or reduction.

Step 6—FGDs sessions organization: An adequate number of FGDs sessions is 2–6 [31,35], and an adequate group size is 4–12 participants [36,37] in each one. In the present research, 13 individuals were invited to one of the two FGDs sessions held—FGD_{sA} and FGD_{sB}. A total of 6 and 7 individuals participated in the two groups A and B, respectively (Tables 1 and 2).

Table 1. Focus Group A—heterogeneous participants' characteristics.

Interviewee Number	Gender	Age (Age Group)	Educational Level	Residence
1	female	18 (18–25)	Secondary	urban
2	male	26 (26–35)	Post-secondary	urban
3	female	53 (46–55)	Secondary	urban
4	male	59 (56–65)	Post-secondary	urban
5	female	57 (56–65)	Primary	rural
6	male	67 (65+)	Tertiary	urban

Table 2. Focus Group B—heterogeneous participants' characteristics.

Interviewee Number	Gender	Age (Age Group)	Educational Level	Residence
1	female	18 (18–25)	Secondary	urban
2	female	55 (46–55)	Secondary	urban
3	female	55 (46–55)	Primary	urban
4	female	59 (56–65)	Primary	rural
5	male	60 (56–65)	Tertiary	urban
6	male	62 (56–65)	Tertiary	urban
7	female	66 (65+)	Primary	rural

Step 7—Selecting and training the coordinator/s: The main and sole coordinator in both FGDs sessions was the researcher—the interviewer—who informed the participants—the interviewees—on the specific issues below [31]:

- There are no right or wrong answers;
- If someone does not understand the question, it will be rephrased;

- Everyone, in turn, will take the floor expressing their personal opinion;
- It will be acceptable to change their opinion after the commentary discussion of each question;
- Comments and answers will be recorded by hand, both by the interviewer and the interviewees;
- The necessity to obtain an oral consent from each participant.

Step 8—Conduct of FGD_S: The two FGDs were conducted over 2 days and during the afternoon hours, as indicated by the bibliography. FGD_{SA} lasted a total of 2 h and 10 min (17:30 p.m. to 19:40 p.m.), and FGD_{SB} lasted a total of 2 h (17:30 p.m. to 19:30 p.m.). A special venue, one of the oldest in the research area, was chosen. The most important criterion in selecting a dedicated space was the maintenance of quietness during the whole interview [27].

Step 9—Data analysis: Data were recorded, coded, and checked, firstly by group and afterward all together [33]. This process was conducted by experts (academics and coordinator) in qualitative research, as required [25]. It is worth noting that the data analysis was based only on the handwritten files mentioned above (steps 4 and 6).

Step 10—Writing the results: For the purpose of this paper, the results will be presented in the Section 3. However, the FGDs results, as part of the large-scale research on HFW carried out, are integrated into the Section 4, in order to provide a better understanding of the statistical results.

3. Results

Thirteen local inhabitants participated in two FGDs. Eight participants were women and five men. Their age ranged from 18 to 67 years. As regards education, four participants were primary school graduates (basic education level), four were high school and post-secondary school graduates (high education), and five were university graduates (higher education). The majority of them (10 participants) lived in an urban center, and only 3 lived in a rural community. However, all of them had lived (in the past) in a rural area for a long time. Hence, they are characterized by rural past and rural memories. The demographic characteristics of the FGDs participants are presented in Table 3.

Table 3. Characteristics of FGDs participants.

Focus Group		Gender	Age (Age Group)	Education Level	Residence Area	Rural Past
$FGDs_A$	1.	female	18 (18–25)	high	urban	yes
	2.	male	26 (26–35)	higher	urban	yes
	3.	female	53 (46–55)	high	urban	yes
	4.	male	59 (56–65)	higher	urban	yes
	5.	female	57 (56–65)	basic	rural	yes
	6.	male	67 (65+)	higher	urban	yes
$FGDs_B$	1.	female	18 (18–25)	high	urban	yes
	2.	female	55 (46–55)	high	urban	yes
	3.	female	55 (46–55)	basic	urban	yes
	4.	female	59 (56–65)	basic	rural	yes
	5.	male	60 (56–65)	higher	urban	yes
	6.	male	62 (56–65)	higher	urban	yes
	7.	female	66 (65+)	basic	rural	yes

3.1. How Demographics Affect HFW

3.1.1. Gender

HFW composition is strictly connected to specific household members. The majority of the participants declared that women are responsible for all the food-related household activities and, consequently, for HFW. Food purchases, cooking, and food storage on household shelves (kitchen, fridge, etc.) are activities that mainly women undertake in

most households in the research area. Nevertheless, a woman is more likely to reheat and eat food leftovers in other meals, seeking out best practices on HFW management, e.g., food and vegetable preservation in the freezer. Furthermore, women are more likely to adopt healthy eating habits as they are interested, more than anyone else, in their appearance. The most noteworthy responses are listed below:

"... my wife cleans the table and does the dishes after each meal ... women do most of the housework ..."

"... I help my mother with food purchases! I drive her to the supermarket twice a month ..." (*laughs*)

"... I am trying to eat healthy ... I am getting older ... it is hard for me to remain slim and healthy."

"... sometimes my children prefer ordering take out to eating the cooked food ..."

"... cooked food is not always consumed on time ... my husband does not like to eat reheated food ..."

3.1.2. Age

The majority of responses indicated that young people are more likely to generate HFW. Their daily routine does not include any household activities, e.g., consumption of leftovers, checking of food labels and food dates, etc. On the contrary, the older age group is more responsible and mature enough to perceive that food waste implies household income in the rubbish. In fact, age differences, especially between young and elderly people, concerning HFW were directly attributed to living conditions (in the past) and experiences. This is evidenced by the following responses:

"... older people lived under difficult circumstances, like wars when they were young ... these people appreciate food more than the young nowadays ..."

"... even in towns, there were not food markets like now ... we can access food almost 24 h a day ..."

"... older people, when they were young had to find, exchange or produce their own food and they also had to manage it in the best way possible ..." *(participants' nodding agreement)*

"... young people today, from the day they are born, have unlimited access to food ... they can go to the supermarket, they can eat snacks and chocolates every day, not only on Sundays or special occasions ... they have grown up without serious problems covering dietary and other basic, daily needs ..."

3.1.3. Residence Area (Rural/Urban)

In urban areas, the modern way of living entails a "distance" between nature and humans, involving limited available time for healthy eating habits, proper food-purchases, and cooking. Instead, in rural areas, there is still time, as well as respect for and awareness of nature. In addition, all the participants come from and/or have lived in a rural area (in the past). They have transferred their rural food-related habits and practices to urban living conditions. Some typical responses about the impact of residential place on HFW composition is presented below:

"... nowadays we can find whatever we want, all year round ... human needs are more demanding than ever and becoming more so"

"... we eat tomatoes only during spring and summer months ..."

"... young people are not close to nature anymore. When I was young, I used to work in our fields, in agriculture ... I know how and when food is produced ..."

"... I grew up in a rural area where we used to give food leftovers to our chickens and dogs. Living in the city now, I only feed birds on my balcony with stale bread ...".

3.1.4. Income and Education

Many of the responses indicated that income and education are two readily connected factors affecting HFW composition. Higher education enables individuals to achieve high

income levels; hence, high-income households are more likely to generate HFW. They can afford new food purchases without paying attention to cost and quantity. They are able to repurchase what they desire, covering their increasing food-related daily needs but within limited time constraints. The following response is an example of a high-income household attitude—a pharmacist working 6 days a week:

"... once a month I go to the supermarket. I have limited time as I have to return to my work ... sometimes I order take out ... I do not have enough energy to cook when I am back home ..."

3.2. How Attitude Has an Impact on HFW

HFW composition is seriously affected by impulse food purchases (multipacks and discounts) and ignorance of food labeling dates—"expiry" and "best before". The available time for cooking has also negatively affected HFW composition. However, rural experiences and lifestyle contribute to a positive attitude preventing and/or reducing HFW composition. Furthermore, "Food Sharing" emerged as a particular habit widespread in rural Greece. Home-grown and/or traditional cooked food, e.g., homemade sweets, pies, etc. is shared among neighbors, friends, relatives, etc., usually using a household kitchen container. The container is not returned empty to the owners but is filled with home-grown or cooked food by the receivers. In the past, rural inhabitants used to promote whatever they produced in their "yard", selling or exchanging their produce in order to cover their essential daily nutritional needs. Since then, "Food Sharing" purposes and motivations have changed. Nowadays, it concerns social and interpersonal relationships preservation and/or development, based on ethical values, mostly among city dwellers who reminisce about the "rural ideal" [36]. Participants' most meaningful responses are listed below:

"... I am looking for discounts and/or multipacks ... that help me save money ..."

"... I feel safe with food labeling dates ... we do not consume food after the "best before" date ..."

"... I do not have enough time to cook every day ... I cook enough twice a week and when someone feels hungry, he/she could find something to eat ..."

"... every year my mother (rural inhabitant) makes a traditional red pepper and tomato sauce and gives me only 1–2 jars ... since I do not have enough storage space in my apartment ... "

"... in my rural residence we used to compost HFW in the courtyard ... now we do not have enough space in our kitchen for a compost bin so we cannot to afford it ..."

"... the town council has to place compost bins in every neighborhood across the city, we need them ..."

"... I give eggs and vegetables from my garden to my daughter ... my grandchildren love their quality and taste ..."

3.3. How Knowledge and Perceptions concerning HFW Are Formed

The feedback also showed that the formed knowledge and perceptions concerning HFW have several impacts. Erroneous or incomplete perceptions were revealed. Participants cannot link their daily dietary and/or consumption choices with the global environmental issues (food miles, climate change, greenhouse effect, etc.). Additionally, the majority of responses revealed a weakness in understanding food labeling dates and the effectiveness of imposing fines on those who waste more than they should. However, economic crises had a positive influence on HFW composition, raising the willingness for prevention and reduction education. This is evidenced by the following responses:

"... I prefer local products ... they are better quality than imported ones ..."

"... I am not responsible for the greenhouse effect ... the sun is ..."

"... I am not responsible for the food waste worldwide ... the supermarkets are ... I have rejected food but not a large quantity ... I am not in the habit of throwing away food ..."

"... "expiry" and "best before" dates are the same information written in other words ..."

"... "expiry" and "best before" dates may indicate something different about packaged food but certainly protect us from spoiled food ..."

"... during the economic crisis I bought the same domestic, quality agricultural products but in smaller quantities"

"... yes, I am interested to learn how to waste less ... it would be very interesting if someone could provide us with information on healthy nutrition and consumption habits ...".

4. Discussion

A plethora of studies are in progress on food wastage issues [2]. The investigation of food losses and waste in different countries around the world, focusing even on specific food types, e.g., tropical fruits [38], entails the necessity to organize and implement guidelines and strategies which will be consistent with sustainable nutrition and consumption [39]. Food wastage studies include economic, environmental, and social aspects which justify their multi-dimensional nature, emphasizing the urgency to examine each case in detail [40,41].

The economic costs at state, business, and household levels; the environmental degradation; and the nutritional-consumption inequalities are the main issues under exploration according to the FAO latest's works [42]. Consumption-households is that stage of the food supply chain where the largest quantities of waste have been recorded [2]. It is an imperative to prevent and/or reduce HFW, and the most indicated manner to achieve this goal is to investigate the factors affecting the HFW composition [43–45]. Therefore, the need for primary data is nowadays extremely important, especially for policy makers, food producers, retailers, and consumers—household members [40,46].

The present paper enriches the global bibliography as there is limited data on HFW in Greece, especially for rural areas [6,47,48]. More accurately, this study focuses on how and why the most common factors that make an impact on HFW composition [49,50] affect the household members using the case of Greece. Gender, age, education, income, and place of residence are the most common factors affecting HFW.

The research reveals a gender dimension in HFW composition. There is an unequal distribution of responsibilities and care initiatives between women and men, with regard to the consumption and eating habits in households. Women are mainly responsible for the daily food-related activities (shopping, cooking, cleaning, tidying, etc.) of their households. Consequently, women often find themselves rejecting and discarding food that was chosen or requested by other members of the household, rather than themselves. This is why the female gender has been directly linked to HFW production. Even in cases where these women lead busy lives, such as having professional obligations, they actively seek ways to manage household food sustainably. Moreover, they show a keen interest in nutrition and health, surpassing that of men. These factors collectively contribute positively to the prevention and/or reduction of HFW. Accordingly, the rural past and experiences have a positive influence on HFW composition. City dwellers who grew up and lived in rural areas have transferred environmentally friendly food-related habits to the urban households where they live now. In an urban environment, a socially constructed rurality has emerged, encompassing social, environmental, and economic interactions among household members. Fast-paced urban lifestyles, influenced by rural experiences, incorporate sustainable consumption and nutritional habits, resulting in reduced food waste and a greater respect for natural resources and farmers' efforts in production. For the first time in an HFW study in Greece, it is crucial to discuss the rural past and experiences.

In addition, two particularly important issues are identified through the current research. The "best before" date is confused with the "expiry" date, which is one of the most serious reasons that edible food ends up in household bins. This confusion is mainly found in food types such as legumes, pasta, cereals, and some dairy products. At the same time, the meaning of food miles, climate change, and greenhouse effect are not perceived, resulting in household members not being able to link their daily consumption and eating habits with global socioecological issues such as HFW. Household members are willing to be informed on the issues above

while local and governmental bodies ought to organize actions designed to provide accurate information, reducing the negative impact on HFW composition.

5. Conclusions

In the present study, an attempt was made to provide valuable information concerning HFW composition. An in-depth methodological approach was applied by collecting qualitative data on HFW factors, causes, and consequences. Two FGDs were conducted, developing a detailed interpretation of HFW in Greece, among rural and urban household members. The method used proved to be a valuable and flexible supplementary research tool in the field of rural sociology, including its application to the HFW issue. The FGDs methodology allows scientists to observe social interactions and explore individual knowledge, perceptions, and attitudes toward food-waste-related issues. In other words, it serves as an effective data collection method allowing scientists to gain insights into consumption and nutritional habits worldwide. This understanding could act as a specific strategic tool for planning and implementing policies, for example, informative campaigns, which could significantly contribute to HFW prevention and/or reduction. Thus, based on the consumption and nutritional specificities of each region, the desired results could first be achieved at the local level. The development of small-scale, local actions is capable of contributing to combating HFW across the country, thereby bringing us closer to achieving the goals of sustainable development.

Further qualitative studies based on the FGDs methodology should be attempted in the future. The innovative methodological tool used in this study offers an opportunity to all the involved parties to reveal special behavioral features and management methods on HFW issues, being customizable for particular geographical areas and/or customer groups.

6. Limitations

The limitations of this research pertain to the methodology, which specifically relies on qualitative research with a small sample size, where individual expressions prevail [36,51]. Furthermore, the results cannot be verified statistically, and they cannot be generalized [52,53]. This research offers findings that could inform future scientific studies. Moreover, the results encourage local authorities to develop strategies and implement informative actions, such as awareness campaigns and the placement of compost bins, to raise awareness of food waste issues.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data will be available upon request by the first author.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Focus group discussion guide.

1. Who wastes the most food in your household? Men or women? Why?
2. Young people and women are mainly interested in nutrient facts in food selection. Contrast, older people and rural residents are interested in qualitative characteristics (e.g., country of origin). Why? 3. The elderly waste less food than the young. Why? 4. Men and young people consume more meat and less fruits than women and older age people. Why? 5. How does income and educational level affect (positive/negative) HFW? Why?
6. Do you use a food shopping list? 7. Why do not you compost food waste at home? 8. Do you waste food from vegetable gardens? 9. Do you consume food after the "use by" date? 10. How much time do you spend cooking/preparing food each day? Is it enough or not? Why? 11. Have you adopted any dietary/consumption habits stemming from your rural household/experience?
12. What is the impact of economic crisis in household food waste management? 13. If fines, regarding food waste prevention/reduction are imposed, what would be fair (€/kg)? 14. How does food transportation and consumption affect the natural environment? 15. What is the connection between climate change, the greenhouse effect and HFW? 16. Is "use by" date the same as "expiry" date? 17. How could we reduce-prevent HFW through voluntary/informative actions?

Table A2. Answer sheet.

Date	
Age	
Residence	Urban/Rural
Education	Primary/Secondary/Post-secondary/Tertiary
Questions	Answers
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	
13	
14	
15	
16	
17	

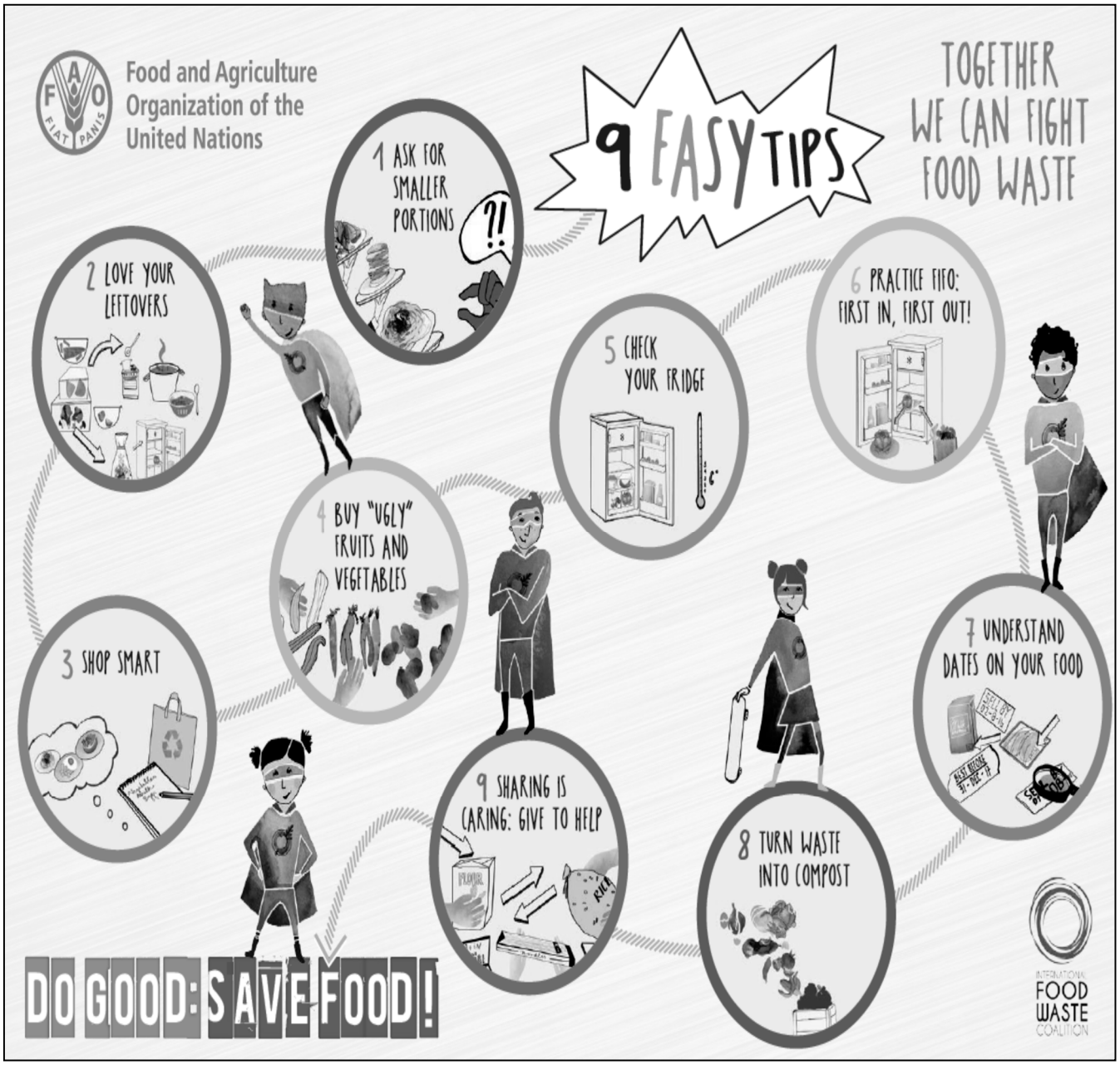


Figure A1. Practical advice about how to reduce HFW [33].

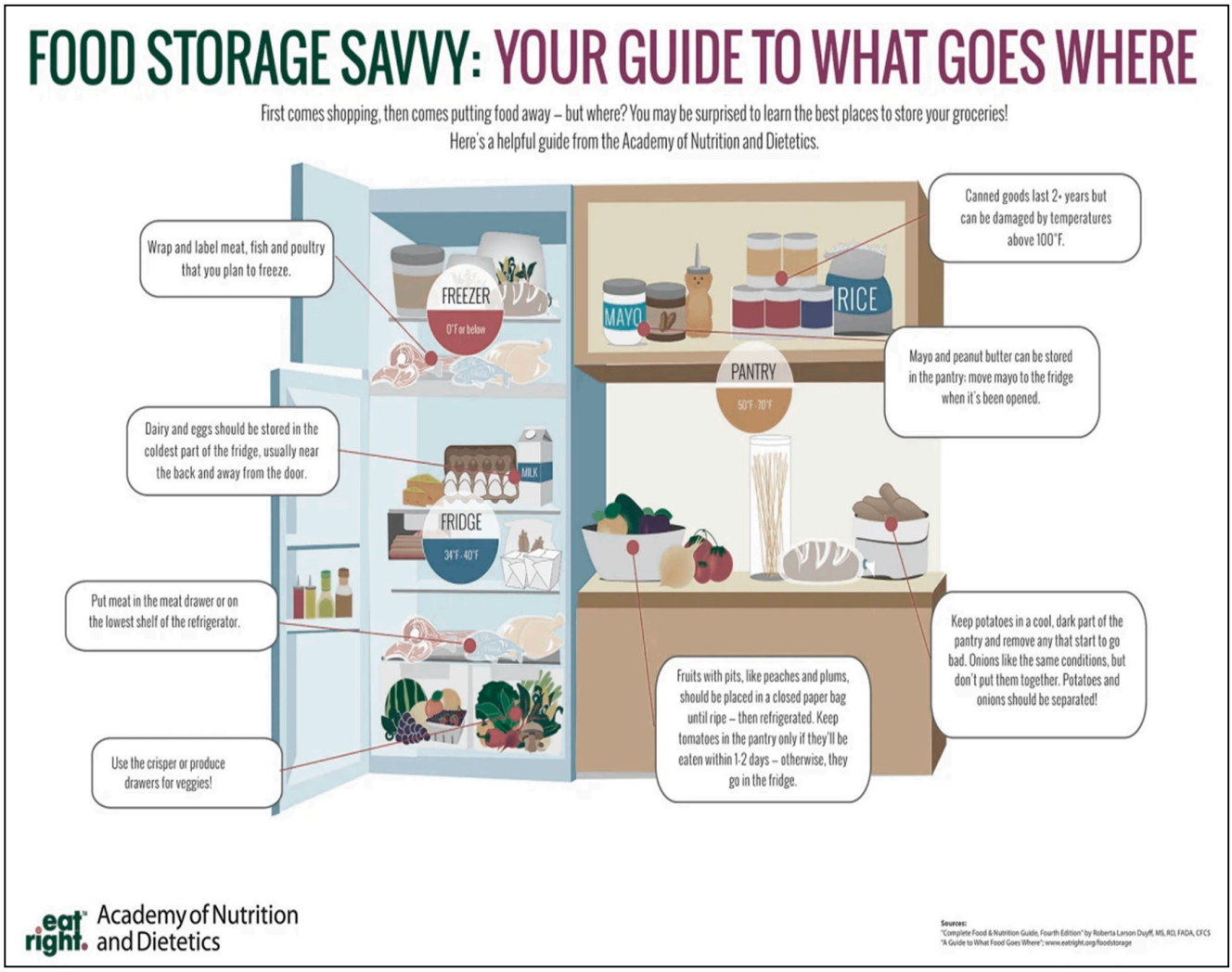


Figure A2. "Every Food on the Right Shelf" [34].

References

1. FAO. *The State of Food and Agriculture. Moving forward on Food Loss and Waste Reduction*; FAO: Rome, Italy, 2019.
2. Parfitt, J.; Barthel, M.; Macnaughton, S. Food waste within food supply chains: Quantification and potential for change to 2050. *Philos. Trans. R. Soc. Lond.* **2010**, *365*, 3065–3081. [CrossRef]
3. FAO. *Energy—Smart Food for People and Climate Issue Paper*; FAO: Rome, Italy, 2011.
4. FAO. *Food Wastage Footprint and Climate Change*; FAO: Rome, Italy, 2015.
5. Hebrok, M.; Heidenstrom, N. Contextualising food waste prevention-decisive moments within every day practices. *J. Clean. Prod.* **2019**, *210*, 1435–1448. [CrossRef]
6. Di Talia, E.; Simeone, M.; ad Scarpato, D. Consumer behaviour types in household food waste. *J. Clean. Prod.* **2019**, *214*, 166–172. [CrossRef]
7. World Bank. Ending Poverty Investing in Opportunity. Washington. 2018. Available online: https://documents.worldbank.org/en/publication/documents-reports/documentdetail/156691570147766895/the-world-bank-annual-report-2019-ending-poverty-investing-in-opportunity (accessed on 11 November 2023).
8. Capone, R.; Bilali, H.; Debs, P.; Bottalico, F.; Cardone, G.; Berjan, S.; Elmenofi, G.; Abouabdillah, A.; Charbel, L.; Arous, S.; et al. Bread and Bakery Products Waste in Selected Mediterranean Arab Countries. *Am. J. Food Nutr.* **2016**, *4*, 40–50.
9. Yildirim, H.; Capone, R.; Karanlik, A.; Bottalico, F.; Debs, P.; Bilali, H. Food Wastage in Turkey: An Exploratory Survey on Household Food Waste. *J. Food Nutr. Res.* **2016**, *4*, 483–489.
10. Abeliotis, K.; Lasaridi, K.; Boikou, K.; Chroni, C. Food waste volume and composition in households in Greece. *Glob. Nest J.* **2019**, *21*, 399–404.
11. Aitsidou, V.; Michailidis, A.; Partalidou, M.; Iakovidou, O. Household food waste management: Socio-ecological dimensions. *Br. Food J.* **2019**, *121*, 2163–2178. [CrossRef]

12. Ananda, J.; Karunasena, G.G.; Mitsis, A.; Kansal, M.; Pearson, D. Analysing behavioural and socio-demographic factors and practices influencing Australian household food waste. *J. Clean. Prod.* **2021**, *306*, 127280. [CrossRef]
13. Schanes, K.; Dobernig, K.; Gözet, B. Food waste matters—A systematic review of household food waste practices and their policy implications. *J. Clean. Prod.* **2018**, *182*, 978–991. [CrossRef]
14. Briault, A. Best Before Isn't an Expiry Date: The Problem of Date Labelling and its Effect on Household Food Waste. *Trail Six* **2018**, *12*, 8.
15. dos Santos, J.I.A.S.; Da Silveira, D.S.; Da Costa, M.F.; Duarte, R.B. Consumer behaviour in relation to food waste: A systematic literature review. *Br. Food J.* **2022**, *124*, 4420–4439. [CrossRef]
16. Aloysius, N.; Ananda, J.; Mitsis, A.; Pearson, D. Why people are bad at leftover food management? A systematic literature review and a framework to analyze household leftover food waste generation behavior. *Appetite* **2023**, *186*, 106577. [CrossRef]
17. Bravi, L.; Francioni, B.; Murmura, F.; Savelli, E. Factors affecting household food waste among young consumers and actions to prevent it. A comparison among UK, Spain and Italy. Resour. Conserv. Recycl. 2020, 153, 104586. *Resour. Conserv. Recycl.* **2020**, *153*, 104586. [CrossRef]
18. European Commission. Household food waste: An individual and national issue. In *Science and Environment Policy*; SCU, Ed.; The University of the West of England: Bristol, UK, 2015.
19. Nikolaus, C.J.; Nickols-Richardson, S.M.; Ellison, B. Wasted food: A qualitative study of U.S. young adults' perceptions, beliefs and behaviors. *Appetite* **2018**, *130*, 70–78. [CrossRef]
20. Cantaragiu, R. The Impact of Gender on Food Waste at the Consumer Level. *Stud. Univ. Vasile Goldis Arad. Econ. Ser.* **2019**, *29*, 41–57. [CrossRef]
21. Quested, T.; Ingle, R.; Parry, A. Household Food and Drink Waste in the United Kingdom 2012. 2013. Available online: https://wrap.org.uk/resources/report/household-food-and-drink-waste-united-kingdom-2012 (accessed on 1 November 2023).
22. Niles, M. Majority of rural residents compost food waste. Policy and Waste Management Implications for rural Regions. *Front. Sustain. Food. Syst.* **2020**, *3*, 123. [CrossRef]
23. Frey, J.H.; Fontana, A. The group interview in social research. *Soc. Sci. J.* **1991**, *28*, 175–187. [CrossRef]
24. Khatun, F.; Saada, S.Y. Focus Group Discussion (FGD). In *Youth Employment in Bangladesh*; Palgrave Macmillan: Singapore, 2020; pp. 77–88.
25. Parsons, V.L. *Stratified Sampling, Wiley StatsRef: Statistics Reference Online*; John Wiley & Sons, Ltd.: Chichester, UK, 2017; pp. 1–11. [CrossRef]
26. Dürrenberger, G.; Behringer, J.; Dahinden, U.; Gerger, Å.; Kasemir, B.; Querol, C.; Schüle, R.; Tabara, D.; Toth, F.; Van Asselt, M.; et al. *Focus Groups in Integrated Assessment—A Manual for a Participatory Tool*; ULYSSES: Dübendorf, Switzerland, 1997; p. WP-97-2.
27. Jayasekara, R.S. Focus groups in nursing research: Methodological perspectives. *Nurs. Outlook* **2012**, *60*, 411–416. [CrossRef]
28. Bernard, R.H. Sampling III: Nonprobability Samples and Choosing Informants. In *Research Methods in Anthropology: Qualitative and Quantitative Approaches*, 6th ed.; The Rowman and Littlefield Publishing Group: Lanham, MD, USA, 2017; pp. 145–161.
29. Palys, T.; in Given, L.M. Qualitative Research Methods. In *The Sage Encyclopedia of Qualitative Research*, 2nd ed.; SAGE: Los Angeles, CA, USA, 2008; pp. 697–698. Available online: http://www.yanchukvladimir.com/docs/Library/Sage%20Encyclopedia%20of%20Qualitative%20Research%20Methods-%202008.pdf (accessed on 8 November 2023).
30. Morgan, D.L. Practical Strategies for Combining Qualitative and Quantitative Methods: Application to Health Research. *Qual. Health Res.* **1998**, *8*, 362–376. [CrossRef]
31. Patel, M.X.; Doku, V.; Tennakoon, L. Challenges in recruitment of research participants. *Adv. Psychiatr. Treat.* **2003**, *9*, 229–238. [CrossRef]
32. Erlingsson, C.; Brysiewicz, P. A hands-on guide to doing content analysis. *Afr. J. Emerg. Med.* **2017**, *7*, 93–99. [CrossRef] [PubMed]
33. FAO. *Do Good Save Food! Together We Can Fight Food Waste: 9 Easy Tips*; FAO: Rome, Italy, 2017.
34. Duyff, L.R. *Complete Food and Nutrition Guide—A Guide to What Food Goes Where*, 4th ed.; Academy of Nutrition and Dietetics: Chicago, IL, USA, 2018; Available online: www.eatingright.org/foodstorage (accessed on 8 November 2023).
35. Guest, G.; Namey, E.; Mckenna, K. How Many Focus Groups Are Enough? Building an Evidence Base for Nonprobability Sample Sizes. *Field Methods* **2017**, *29*, 3–22. [CrossRef]
36. Shucksmith, M. Re-imagining the rural: From rural idyll to Good Countryside. *J. Rural Stud.* **2018**, *59*, 163–172. [CrossRef]
37. Kruger, R.A.; Casey, M.A. *Focus Groups: A Practical Guide for Applied Research*, 3rd ed.; Saga: Thousand Oaks, CA, USA, 2000.
38. Tansuchat, R.; Pankasemsuk, T.; Panmanee, C.; Rattanasamakarn, T.; Palason, K. Analyzing Food Loss in the Fresh Longan Supply Chain: Evidence from Field Survey Measurements. *Agriculture* **2023**, *13*, 1951. [CrossRef]
39. Braun, J.; Afsana, K.; Fresco, L.O.; Ali Hassan, M.H. *Science and Innovations for Food Systems Transformation*; Springer: Berlin/Heidelberg, Germany, 2023; pp. 59–86.
40. Shafiee-Jood, M.; Ximing, C. Reducing food loss and waste to enhance food security and environmental sustainability. *Environ. Sci. Technol.* **2016**, *50*, 8432–8443. [CrossRef] [PubMed]
41. Toti, E.; Di Mattia, C.; Serafini, M. Metabolic Food Waste and Ecological Impact of Obesity in FAO World's Region. *Front. Nutr.* **2019**, *6*, 126. [CrossRef] [PubMed]
42. Mokrane, S.; Buonocore, E.; Capone, R.; Franzese, P.P. Exploring the Global Scientific Literature on Food Waste and Loss. *Sustainability* **2023**, *15*, 4757. [CrossRef]

43. Ajzen, I. The theory of planned behavior. *Organ. Behav. Hum. Decis. Process.* **1991**, *50*, 179–211. [CrossRef]
44. Hebrok, M.; Bok, C. Household food waste: Drivers and potential intervention points for design—An extensive review. *J. Clean. Prod.* **2017**, *151*, 380–392. [CrossRef]
45. Romani, S.; Grappi, S.; Bagozzi, R.P.; Barone, A.M. Domestic food practices: A study of food management behaviors and the role of food preparation planning in reducing waste. *Appetite* **2018**, *121*, 215–227. [CrossRef]
46. Durán-Sandoval, D.; Durán-Romero, G.; Uleri, F. How Much Food Loss and Waste Do Countries with Problems with Food Security Generate? *Agriculture* **2023**, *13*, 966. [CrossRef]
47. Cathcart, E.P.; Murray, A.M. A note on the percentage loss of calories as waste on ordinary mixed diets. *J. Hyg.* **1939**, *39*, 45–50. [CrossRef] [PubMed]
48. Li, Y.; Wang, L.; Liu, G.; Cheng, S. Rural household food waste characteristics and driving factors in China. *Resour. Conserv. Recycl.* **2021**, *164*, 105209. [CrossRef]
49. Chen, M.-F. Integrating the extended theory of planned behavior model and the food-related routines to explain food waste behavior. *Br. Food J.* **2023**, *125*, 645–661. [CrossRef]
50. Principato, L.; Mattia, G.; Leo, D.A.; Pratesi, C.A. The household wasteful behaviour framework: A systematic review of consumer food waste. *Ind. Mark. Manag.* **2021**, *93*, 641–649. [CrossRef]
51. Siemieniako, D.; Kubaci, K. Female students' drinking seen through collages and diaries. *Qual. Mark. Res. Int. J.* **2013**, *16*, 296–314. [CrossRef]
52. Anderson, C. Presenting and evaluating qualitative research. *Am. J. Pharm. Educ. Am. Assoc. Coll. Pharm.* **2010**, *74*, 141. [CrossRef]
53. Freitas, H.; Oliveira, M.; Jenkins, M.; Popjoy, O. *The Focus Group, a Qualitative Research Method, Reviewing the Theory, and Providing Guidelines to Its Planning*; ISRC Working Paper 010298; University of Baltimore: Baltimore, MD, USA, 1998.

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Article

The Regionally Heterogeneous Impact of China's Environmental Regulation on the Transformation and Upgrading of Its Industrial Structure

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Abstract: Approaches to promoting the transformation and upgrading of China's industrial structure represent an important issue in high-quality economic development. The upgrading of industrial structures is beneficial not only for environmental protection but also for sustainable economic development. This article first tests the correlation between environmental regulation and the transformation and upgrading of industrial structure through an impulse response function and then uses provincial panel data to analyze the regionally heterogeneous impact of environmental regulation on industrial structure upgrading. The research results indicate that: (1) the presented impulse response graph indicates that environmental regulation shocks have a significant impact on the rationalization and upgrading of industrial structure, and subsequent variance decomposition indicates that environmental regulation has a strong explanatory power on the transformation and upgrading of industrial structure; (2) overall, strengthening the level of environmental regulation is not conducive to the rationalization of industrial structure (RIS), but a strong level of environmental regulation can significantly promote the upgrading of industrial structure (UIS); and (3) at the regional level, there is significant regional heterogeneity in the impact of environmental regulation on the transformation and upgrading of industrial structure in different regions. Environmental regulation can promote UIS in China's eastern and western regions, but it is not conducive to RIS. Environmental regulation can promote RIS in China's central region, but it has a negative impact on UIS. The conclusion of this article provides inspiration for sustainable economic development.

Keywords: environmental regulation; industrial structure; regional heterogeneity

1. Introduction

After more than 40 years of sustained high-speed growth, the Chinese economy has entered a stage of high-quality growth. In this new era, accelerating the transformation and upgrading of industrial structure is an important measure in promoting high-quality economic growth. In fact, the process of industrial structure transformation and upgrading is the core driving force of China's economic growth and is related to whether China can overcome the middle-income trap. However, the upgrading of China's industrial structure faces dual constraints of "high pollution" and "structural adjustment". On the one hand, the long-term development model of "high energy consumption" and "high emissions" has brought about excessive resource consumption and serious degradation of the ecological environment. On the other hand, there are problems in China's industrial structure, such as weak independent research and development capabilities and homogenization of regional industrial structures, leading to oversupply in middle and low-end sectors. In this situation, the analysis of approaches to balancing the transformation and upgrading of China's industrial structure with environmental pollution and the promotion of high-quality economic development are of great practical significance.

Problems related to environmental pollution force China's government to actively intervene by means of environmental regulation, in order to solve the dual dilemma of "high pollution" and "structural adjustment", and achieve sustainable economic development. However, in the face of increasingly strict environmental regulations formulated by the central government, local governments at all levels may relax the standards associated with environmental regulation policy implementation or even choose not to implement them in an attempt to avoid decreases in their own fiscal revenue, leading to a trend of "bottom-up competition" in environmental regulation. Due to the severe environmental constraints and structural adjustment difficulties faced by China's industrial development, as well as the differences in resource endowments and varying levels of development in different regions, a deep analysis of the regionally heterogeneous impact of environmental regulation on the transformation and upgrading of China's industrial structure is of great significance in enhancing local environmental protection momentum and promoting high-quality industrial development.

In this article, the correlation between environmental regulation and industrial structure transformation and upgrading is tested by utilizing a panel vector autoregressive model. The research results show that environmental regulation has a significant impact on industrial structure transformation and upgrading. Specifically, the impact of environmental regulation shocks on the rationalization of industrial structure is significant, reaching 37.75%, and the contribution of variance of environmental regulation shocks to the upgrading of industrial structure is 23.65%. We further utilize dynamic panel models to analyze the regionally heterogeneous impact of China's environmental regulation on the advancement of its industrial structure upgrading. The test results indicate that environmental regulations are not conducive to the rationalization of industrial structure but are conducive to its upgrading. At the same time, the impact of environmental regulation on industrial structure upgrading shows obvious characteristics of regional heterogeneity.

2. Literature Review

The "three highs and one low" caused by the traditional development model poses great challenges to the high-quality growth of the Chinese economy, and industrial structural adjustment has become an inevitable trend of development. Therefore, approaches to promoting the transformation and upgrading of China's industrial structure have come to represent an important issue in high-quality economic development [1,2]. The famous Porter hypothesis points out that appropriate environmental regulations can stimulate technological innovation in enterprises, offset the production costs that environmental regulations may bring by increasing productivity, and achieve the dual goals of industrial upgrading and environmental improvement [3–5]. Numerous publications in the literature have analyzed whether the Porter hypothesis is established in China, and several studies have verified the significant role of environmental regulation in upgrading industrial structure in China [6,7]. However, it is worth noting that, due to China's vast territory and practical constraints such as differentiated resource endowments and uneven development levels in various regions, one cannot help but consider whether the above factors will lead to a heterogeneous impact of environmental regulation on industrial structure upgrading in China. Therefore, the focus of this article is on whether there are characteristics of heterogeneity in the impact of China's environmental regulation on the upgrading of its industrial structure.

Although most studies support the Porter hypothesis and verify the positive role of environmental regulation in industrial structure upgrading in China, it cannot be ignored that there are also numerous studies based on the perspective of economic development, and empirical results do not support the Porter hypothesis [8,9]. The main theoretical support for this type of research is the pollution shelter hypothesis. This theory suggests that developing countries, when prioritizing economic development, tend to overlook environmental protection to some extent. Therefore, developing countries with abundant environmental resources receive highly polluting industries from developed countries and

become clusters of polluting industries. Wang et al. (2019) used Chinese enterprise data from 2011 to 2015 to empirically test the impact of environmental regulation on the location selection of polluting enterprises. The empirical results proved that environmental regulations do indeed affect the location selection of polluting industry enterprises [10]. Dou and Han (2019) studied the transfer of polluting industries in China from the perspective of industrial mobility and conducted empirical analysis based on provincial-level data from 2000 to 2015. The research results showed that polluting industries with strong liquidity tend to shift directly to areas with loose regulation, ultimately leading to the outward transfer of polluting industries, thus verifying the pollution shelter hypothesis [11].

However, some research findings do not support the pollution shelter hypothesis. Marconi (2012) used the changes in bilateral trade structure between China and 14 EU countries between 1996 and 2006 as a measure of comparative advantage. The research found that after controlling for some variables, no evidence was found to suggest that pollution shelter had an impact on the bilateral trade patterns between Europe and China [12]. Zheng and Shi (2017) used panel data from 30 provinces in China from 2004 to 2013 to empirically test whether different environmental regulations affect the domestic transfer of polluting industries in China. The empirical results indicate that differentiated environmental regulations can lead to the geographical transfer of polluting industries, and the effectiveness of the pollution shelter hypothesis is closely related to the type of environmental policy. Specifically, policies such as pollution discharge fees and environmental complaints encourage industrial transfer, while environmental policies such as laws and regulations prevent the transfer of polluting industries to other regions [13]. There are many reasons for the diversity of research conclusions, including differences in empirical methods [14–16] and differences in research perspectives [17–19], leading to a lack of consistent research conclusions.

On the basis of a proposed impact of environmental regulation on industrial structure upgrading—one that is effectively reversed—relevant research further studies the dynamic and nonlinear effects of its effects [20–23]. Chen et al. (2019) used the PSTR model to analyze the dynamic correlation mechanism between China's environmental regulation policies and industrial structure upgrading, and the research results found that there was a significant nonlinear characteristic between the two. The research results indicate that the relationship between China's environmental regulation policies and industrial structure upgrading is dynamic, and the dynamic nature of policies' effects cannot be ignored when formulating environmental policies [24]. Chen et al. (2022) empirically analyzed the impact of informal environmental regulations on industrial structure upgrading based on provincial-level data in China from 2000 to 2016. The research results indicate that informal environmental regulations have a significant positive impact on industrial structure upgrading and that there is also a significant threshold effect [25]. The research conclusion greatly enriches the utility of policies in stimulating industrial structure upgrading. In addition, there is also a wealth of works in the literature exploring other factors that affect industrial structure upgrading, greatly expanding the research boundaries of industrial economics [26–30].

Regarding the above literature review, it can be said that there has been extensive research on environmental regulation and industrial structure upgrading, but there is little research on the regionally heterogeneous impact of China's environmental regulation on industrial structure upgrading based on the fact that the country has a vast territory and different natural endowments in different regions. The regionally heterogeneous impact of environmental regulation refers to the inconsistent effects resulting from the implementation of identical environmental regulation policies in different regions on the upgrading of their respective industrial structures. An important implication of this impact is that the Chinese government should not adopt a one-size-fits-all mode when formulating environmental policies. Based on this, this article re-examines the effectiveness and heterogeneity of environmental regulation in China in order to provide new empirical evidence for policy authorities to formulate environmental regulation policies, constituting an important marginal contribution of this article.

Ensuring sustainable development is an important goal pursued by policy authorities, and the transformation and upgrading of industrial structure is necessary to achieve sustainable development. Therefore, it is particularly important to examine the factors promoting industrial upgrading. There have been numerous studies exploring the impact of tradition [31–33], but due to the constraints of insufficient policy space, the effectiveness of these tools has been greatly reduced. What impact will environmental policies, as effective supplements to traditional tools, have on industrial structure? Will they promote the upgrading of industrial structure and ensure sustainable economic development? This type of issue deserves in-depth research, with the aim of injecting new policy vitality into sustainable development. Therefore, this article examines the impact of environmental policies on the transformation and upgrading of industrial structure under the goal of sustainable development, in order to provide solid empirical evidence toward optimizing economic structure and achieving sustainable development.

3. Empirical Analysis of Environmental Regulation and Industrial Structure

3.1. Measurement of Industrial Structure Upgrading Indicators

China has a vast territory and significant differences in economic development across different regions. Overall, the transformation and upgrading of China's industrial structure have garnered significant achievements in recent years. However, from a regional perspective, there are significant differences in the effects of environmental regulation on industrial structure upgrading in different regions. The eastern, central, and western regions of China face different environmental pressures and industrial structure transformation and upgrading. The green adjustment of industrial structures represents an important approach to addressing the deterioration of the ecological environment and stable economic growth. From a dynamic perspective, the transformation and upgrading of industrial structure represent the process of achieving the upgrading and rationalization of industrial structure. This article mainly measures the degree of industrial structure transformation and upgrading across two dimensions: rationalization of industrial structure (RIS) and upgrading of industrial structure (UIS).

Due to different understandings of the connotations of RIS in the academic community, the indicators selected are also different in their understanding. In fact, there is still no unified standard in the academic community for RIS. RIS not only reflects the ability of inter-industry structural transformation but also reflects the degree of effective resource utilization and is a measure of the coordination between factor input and output structure [34]. In terms of this degree of coordination, researchers generally use the degree of structural deviation to measure RIS, but this indicator considers the economic status of China's three main industries to be equal, ignoring the importance of different industries in the economy [35]. To measure the level of RIS in various regions, this article selects the Thiel index, which takes into account the deviation between the output and employment structures of each industry as well as the differences in economic status of each industry [36]. The specific calculation formula is as follows:

$$TL = \sum_{m=1}^{3} \left(\frac{Y_m}{Y} \right) \ln \left(\frac{Y_m}{L_m} / \frac{Y}{L} \right) \quad m = 1, 2, 3 \tag{1}$$

In the above equation, TL represents the Theil index, Y represents the gross domestic product of each region, L represents the total employment of each region, Y_m represents the output value of the three major industries in each region, L_m represents the employment of the three major industries, and m represents the three major industries themselves. The Thiel index can better reflect the output and employment structures of China's three major industries. According to the definition, when $TL = 0$, the economy is in an equilibrium state, with coordinated development among various sectors of the national economy and a high degree of RIS. The larger the TL value, the easier it is for economic development to

deviate from equilibrium, and the industrial structure is unreasonable. It is necessary to allocate production factors reasonably to promote coordinated industrial development.

UIS is an important component of industrial structure upgrading, reflecting the dynamic evolution process of industrial structure from low level to high level at different economic development levels and stages. According to Clark's law, the literature defines UIS as the increase in the proportion of non-agricultural output value, but this traditional measurement method that only focuses on increases in the contribution of industrial output cannot accurately reflect the essence of industrial structure evolution. UIS involves the evolution of the proportional relationship between industries and the improvement of labor productivity. A larger share of industries with higher labor productivity in an economy indicates a higher level of UIS. This article refers to the approach of Liu Wei et al. (2008) [37] and defines UIS as the product of the proportional relationship between industries and industrial labor productivity. The specific calculation formula is as follows:

$$ES = \sum_{m=1}^{3} \frac{Y_m}{Y} \times LP_m,\ m = 1, 2, 3 \tag{2}$$

In the formula, ES represents UIS, Y is as explained above, and LP_m represents the labor productivity of China's three major industries in each region, obtained by using the ratio of the added value of the regional industry to the number of employed people, measured at the end of the same period. If the ES value is on the rise, it means that the overall development level of the industry is constantly improving and the associated industrial structure is in the process of upgrading.

3.2. Impulse Response Analysis

In order to explore the correlation between environmental regulation and industrial structure transformation and upgrading, this section establishes a panel vector autoregressive model (referred to as PVAR). The PVAR model does not need to set causal relationships between variables in advance but instead treats all variables in the system as endogenous variables, analyzing the impact of each variable and its lagged variables on other variables in the model. The general expression of the model is as follows:

$$\begin{array}{l} Y_{it} = Y_{it-1}A_1 + Y_{it-2}A_2 + \cdots + Y_{it-p+1}A_{p-1} + Y_{it-p}A_p + u_i + e_{it} \\ i \in \{1, 2, \ldots N\}, t \in \{1, 2, \ldots, T_i\} \end{array} \tag{3}$$

In the expression above, Y_{it} is a $(1 \times k)$-dimensional vector, u_i is the individual fixed effect of the cross section, e_{it} is the error perturbation term, and matrices $A_1, A_2, \ldots A_{p-1}, A_p$ are coefficients to be estimated. This section selects 29 provinces (cities and regions) in China (excluding Xizang, Qinghai, Hong Kong, Macao, and Taiwan due to lack of data) as indicators to establish PVAR models; data from 2004 to 2021 are considered.

The PVAR model requires variables to have stationarity, and non-stationary data lead to the phenomenon of pseudo-regression. This article first conducts a stationarity test on panel data. In order to ensure the effectiveness of the unit root of the panel, this article adopts three methods, namely the LLC test, the IPS test, and the ADF–Fisher test, to test the stationarity of the panel data, in order to overcome the errors that may arise from a single test method. This study used the above three methods to conduct unit root tests on RIS, UIS, and environmental regulation variables; the results are shown in Table 1. All variables significantly rejected the null hypothesis containing unit roots at the 1% level, thus indicating that the data are stationary. Here, we assert that the figures and tables presented in this paper are calculated by the authors and there is no possibility of copying the results of others. To avoid repetition, we do not elaborate further on each figure or table in the following text.

Table 1. Unit root test results.

Variable	LLC t-Value	Ips t-Bar	ADF–Fisher			
			P	Z	L	Pm
TL	−13.5874 ***	−13.3130 ***	97.6505 ***	−6.7029 ***	−7.5516 ***	10.6305 ***
ES	−13.0592 ***	−13.5865 ***	118.9495 ***	−7.8894 ***	−9.4195 ***	13.7084 ***
ER	−10.7883 ***	−11.4245 ***	49.9767 ***	−2.7543 ***	−2.9287 ***	3.7494 ***

Note: *** indicates rejection of the original hypothesis of the existence of unit roots at a significance level of 1%.

According to the results in Table 1, it can be seen that environmental regulation, RIS, and UIS form a stable panel sequence. An additional PVAR model is constructed to analyze the relationship between environmental regulation and industrial structure transformation and upgrading. The model settings are as follows:

$$\begin{bmatrix} TL_{it} \\ ES_{it} \\ ER_{it} \end{bmatrix} = \begin{bmatrix} \beta_{10} \\ \beta_{20} \\ \beta_{30} \end{bmatrix} + \sum_{j=1}^{p} \begin{bmatrix} a_{11}^{j} & a_{12}^{j} & a_{13}^{j} \\ a_{21}^{j} & a_{22}^{j} & a_{23}^{j} \\ a_{31}^{j} & a_{32}^{j} & a_{33}^{j} \end{bmatrix} \begin{bmatrix} TL_{it-j} \\ ES_{it-j} \\ ER_{it-j} \end{bmatrix} + \begin{bmatrix} u_{1i} \\ u_{2i} \\ u_{3i} \end{bmatrix} + \begin{bmatrix} \varepsilon_{1it} \\ \varepsilon_{2it} \\ \varepsilon_{3it} \end{bmatrix} \quad (4)$$

The subscripts i and t represent each province, city, and observation year, respectively. p represents the lag order of the model, u_i represents unobservable fixed effects, and ε_{it} represents the error perturbation term. The PVAR model must determine the optimal lag order, which is determined according to AIC, BIC, and HQIC. The results shown in Table 2 consistently indicate that the optimal lag order of the model is 2, that is, p in the model is equal to 2.

Table 2. PVAR lag order test results.

Lag Order	AIC	BIC	HQIC
Lagging one period	109.4901	10.5941	69.8609
Lagging two periods	71.1443 *	5.2110 *	44.7222 *
Lagging three periods	73.8405	40.8738	60.6294

Note: * represents the lag order selected based on information criteria.

This article uses the generalized moment estimation method (GMM) to estimate the model. After 500 Monte Carlo simulations, a consistent estimation of the PVAR model is obtained, as shown in Table 3.

Table 3. GMM estimation results of the model.

Variables	*TL*		*ES*		*ER*	
TL (−1)	0.2611 **	(2.41)	−0.2353 *	(−1.68)	0.8473 ***	(3.87)
ES (−1)	−0.0799 ***	(−4.02)	0.1609 ***	(3.01)	−0.2330 ***	(−4.00)
ER (−1)	−0.0551 **	(−2.14)	0.2960 ***	(4.36)	−0.1333	(−1.32)
TL (−2)	0.5713 ***	(7.72)	−0.6762 ***	(−3.29)	1.6557 ***	(6.68)
ES (−2)	−0.0040	(−0.23)	−0.0806	(−1.63)	0.1119 *	(1.83)
ER (−2)	−0.1007 ***	(−3.23)	−1.1919 *	(−1.18)	−0.5436 ***	(−4.81)

Note: The values in parentheses are z values, and ***, **, and * represent significant values at 1%, 5%, and 10% confidence levels, respectively.

In order to more intuitively describe the correlation between variables, an impulse response function (IRF) is selected for analysis. An impulse response function can describe the response of an endogenous variable to the shock brought by an error term. Figure 1 shows impulse response curves depicting the responses of *TL* and *ES* to environmental regulation (*ER*). The solid black line in the middle represents the response function curve, and the gray area represents the confidence interval of twice the standard deviation.

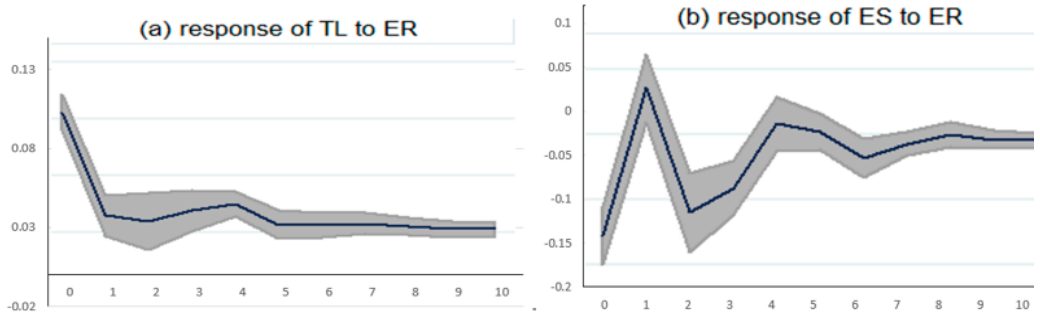


Figure 1. Impulse response curves.

From the impulse response estimation results in Figure 1, it can be observed that there is a significant lag in the impact of environmental regulation on the transformation and upgrading of China's industrial structure. Firstly, looking at (a) in Figure 1, if *ER* is subjected to a standard deviation shock in a given period, *TL* has a strong response in the same period, with the positive response value reaching its maximum. Subsequently, the degree of impact decreases significantly, with small fluctuations and a gradual decrease in periods 3–5. At the end of the period, it gradually weakens, almost to zero. Next, we turn to (b) in Figure 1. In a given period, when *ER* is subjected to a standard deviation shock, *ES* has a strong response in the same period, with the negative response reaching its maximum and then showing an upward trend. It reaches its peak in the first period and then drops back to a negative value in the second period. The impact of the shock gradually decreases in periods 3–5 and converges to 0 around the 10th period. In summary, environmental regulation shocks have an impact on both RIS and UIS. Environmental regulation shocks have a positive impact on RIS, while their impact on UIS is relatively complex, initially having a negative impact followed by a positive impact and, in the long run, the degree of impact decreases and stabilizes.

Next, the variance decomposition method is used to obtain the degree of impact of environmental regulation shocks on industrial structure transformation and upgrading in different VAR equations for the sake of accurate characterization and examination. Table 4 lists the variance decomposition results for the first, fifth, and tenth prediction periods.

Table 4. Analysis of variance results.

Variables	Periods	*ER*	*TL*	*ES*
ER	1	1.0000	0.0000	0.0000
	5	0.7879	0.1832	0.0289
	10	0.7720	0.1926	0.0354
TL	1	0.4863	0.5137	0.0000
	5	0.3854	0.5770	0.0376
	10	0.3775	0.5832	0.0393
ES	1	0.1401	0.0298	0.8301
	5	0.2337	0.0780	0.6883
	10	0.2365	0.0863	0.6772

Note: The results were obtained through Monte Carlo simulation 200 times.

The following is shown in Table 4: (1) environmental regulation shocks are significantly influenced by themselves, with a variance contribution of 77.2% to their own fluctuations. UIS and RIS are also sources of environmental regulation fluctuations, but the impact is relatively small: 19.26% and 3.54%, respectively; (2) RIS is mainly influenced by its own impact, while the impact of environmental regulation has a significant contribution to RIS, reaching 37.75%, indicating that RIS is highly impacted by environmental regulation; and (3) the variance contribution of environmental regulation shocks to UIS reached 23.65%, and the variance contribution rate of RIS shocks to UIS was 8.63%. This also proves that RIS is a prerequisite for achieving UIS [38].

4. Methodology

4.1. Model Settings

To test the impact of environmental regulation on the transformation and upgrading of China's industrial structure, the following static panel data model is first established:

$$\begin{aligned} TL_{it} &= \alpha_0 + \alpha_1 ER_{it} + \alpha_2 Pgdp_{it} \\ &+ \alpha_3 Urban_{it} + \alpha_4 Fiscal_{it} + \alpha_5 Open_{it} + \alpha_6 Edu_{it} + \mu_i + \eta_t + \varepsilon_{it} \end{aligned} \tag{5}$$

$$\begin{aligned} ES_{it} &= \beta_0 + \beta_1 ER_{it} + \beta_2 Pgdp_{it} \\ &+ \beta_3 Urban_{it} + \beta_4 Fiscal_{it} + \beta_5 Open_{it} + \beta_6 Edu_{it} + \mu_i + \eta_t + \varepsilon_{it} \end{aligned} \tag{6}$$

In the above expressions, the subscripts $i = 1, 2, 3 \ldots 29$ represent various provinces and cities in China, $t = 1, 2, 3 \ldots$ represents the period, and TL_{it}, ES_{it}, ER_{it} $Pgdp_{it}$, $Urban_{it}$, $Fiscal_{it}$, $Open_{it}$, and Edu_{it} represent the RIS, UIS, environmental regulation, economic development, urbanization process, fiscal freedom, openness to the outside world, and human capital level of the *i-th* province's *t-th* period; μ_i is the individual effect, η_t is the time effect, and ε_{it} is a random error term.

For static models (5) and (6), fixed-effects models or random-effects models are usually chosen to obtain estimation results. Compared to fixed-effects models, random-effects models are relatively more effective but require that exogenous variables are not related to individual effects. Fixed-effects models do not require exogenous variables or individual fixed effects but they consume more degrees of freedom, and each fixed-effects model has its own advantages and disadvantages when used. This article uses the Hausman test method to determine which estimation method to choose. Meanwhile, due to the frequent issues of heteroscedasticity and autocorrelation encountered in panel data model estimation, this paper tests this and further uses the FGLS estimation method to estimate the model.

It is worth noting that models (5) and (6) implicitly assume that RIS and UIS undergo immediate changes with changes in control variables: there is no lag effect between the two. In fact, any economic factor change itself has a certain inertia, and early results often have an impact on the later period [39]. The adjustment of many factors that affect the transformation and upgrading of industrial structure, such as energy structure, consumption structure, and urbanization development level, is long-term and slow. The sensitivity of industrial structure transformation and upgrading to these macro-factors also determines the lag associated with industrial structure transformation and upgrading. At the same time, the transformation and upgrading of industrial structure are a sublation of the original industrial structure, which, to some extent, represents selective retention and development. The current situation of RIS and UIS is the result of preserving and developing earlier versions of the industrial structure. Early stages of RIS and UIS have lagging effects on later stages of RIS and UIS. Based on this, this article introduces the following dynamic panel model:

$$\begin{aligned} TL_{it} &= \alpha_0 + \lambda_0 TL_{i(t-1)} + \alpha_1 ER_{it} + \alpha_2 Pgdp_{it} \\ &+ \alpha_3 Urban_{it} + \alpha_4 Fiscal_{it} + \alpha_5 Open_{it} + \alpha_6 Edu_{it} + \mu_i + \eta_t + \varepsilon_{it} \end{aligned} \tag{7}$$

$$\begin{aligned} ES_{it} &= \beta_0 + \lambda_1 ES_{i(t-1)} + \beta_1 ER_{it} + \beta_2 Pgdp_{it} \\ &+ \beta_3 Urban_{it} + \beta_4 Fiscal_{it} + \beta_5 Open_{it} + \beta_6 Edu_{it} + \mu_i + \eta_t + \varepsilon_{it} \end{aligned} \tag{8}$$

In the above expressions, $TL_{i(t-1)}$ is the first-order lag term of TL_{it}, $ES_{i(t-1)}$ is the first-order lag term of ES_{it}, and the adjustment coefficient λ represents the impact of the rationalization and upgrading of the previous industrial structure on the current period.

It is worth emphasizing that for dynamic panel models (7) and (8), due to endogeneity issues, both random- and fixed-effects estimators are biased, so instrumental variables are needed for estimation. The instrumental variable method requires the selected instrumental variable to be related to the variable it is replacing and independent of the random error term. In fact, due to the lack of uniqueness in the selection of instrumental variables and the

unobservability of random error terms, it is difficult to find suitable instrumental variables to estimate the model.

In response to this issue, Arellano and Bond (1991) [40] proposed the differential generalized moment estimation method (Difference GMM), which first performs a first-order difference on the estimation equation and then uses the lag value of the explanatory variable as the instrumental variable. However, research has shown that there is a weak instrumental variable problem in differential generalized moment estimation, resulting in estimation bias. To address this issue, Blundell and Bond (1998) [41] proposed the system generalized moment estimation method. System generalized moment estimation estimates the difference equation and the level equation as a system. Compared to differential generalized moment estimation, system generalized moment estimation is more effective. This article uses system generalized moment estimation to estimate dynamic models (7) and (8).

4.2. Variables and Data

Explanatory variable: The explanatory variable of this article is the level of industrial structure upgrading, mainly measured across two dimensions: RIS and UIS. Please refer to the above text for the specific calculation method.

Core explanatory variable: The core explanatory variable of this article is the level of environmental regulation, and there are various methods proposed in existing publications within in literature related to the measurement of environmental regulation variables. This article adopts the comprehensive index method to construct environmental regulatory indicators. The specific approach is to select four individual indicators, namely sulfur dioxide removal rate, industrial smoke, dust removal rate, and comprehensive utilization rate of industrial solid waste, and weight them to obtain environmental regulatory indicators.

Control variables: Referring to the work of Jin and Shen (2018) [42], the following variables were introduced as control variables: economic development level ($Pgdp$), urbanization process ($Urban$), fiscal freedom ($Fiscal$), openness to the outside world ($Open$), and human capital level (Edu). The selection and calculation method of control variables in this article are shown in Table 5.

Table 5. Control variables and calculation methods.

Variables	Calculation Methods
Pgdp	Per capita gross regional product
Urban	Ratio of urban population to total population at the end of the year in the region
Fiscal	Ratio of government public fiscal revenue to fiscal expenditure
Open	Ratio of foreign direct investment stock to regional GDP
Edu	Per capita education years for population aged 6 and above

This paper uses panel data from 29 provinces and cities in China from 2004 to 2021 (excluding Xizang, Qinghai, Hong Kong, Macao, and Taiwan due to lack of data) to study the impact of China's environmental regulation implementation on the transformation and upgrading of its industrial structure. The required raw data were obtained from the China Environmental Yearbook, the China Industrial Statistical Yearbook, the China Economic Network Statistical Database, and the China Statistical Yearbook. The price index indicators mentioned in this article have been adjusted to constant prices based on the year 2004, and the descriptive statistics of the variables are shown in Table 6.

Table 6. Statistical description of variables.

Variables	Mean	SD	Min	Max
TL	0.2484	0.1534	0.0161	0.8771
ES	0.7660	0.5090	0.0939	2.8188
ER	0.0041	0.0034	0.0004	0.0285
Pgdp	9.9567	0.5686	8.3703	11.1634
Urban	0.3948	0.1725	0.1576	0.9032
Fiscal	0.5317	0.1872	0.2306	0.9509
Open	1.9793	2.1058	0.2478	14.0070
Edu	8.6315	0.9672	6.3778	12.0807

5. Empirical Analysis

In order to investigate whether there is substantial multicollinearity in the econometric model, this article uses a stepwise regression method to estimate the dynamic panel models (7) and (8). At the same time, the system generalized moment estimation method is used to regress the dynamic panel to solve the endogeneity problem in the model, and the *Sargan test* and the *Arellano Bond test* are used to identify the effectiveness of instrumental variables and the rationality of model settings. Among them, the *Sargan test* is used to test whether there is an overidentification problem, that is, to test whether all instrumental variables are valid. The original assumption was that all instrumental variables are valid. The *Arellano Bond test* is divided into two types: AR (1) and AR (2), which are used to test whether the disturbance term has first-order and second-order autocorrelation. The original assumption was that there is no autocorrelation.

5.1. Estimation Results of Environmental Regulation on RIS at the National Level

Full-sample estimation results of the impact of China's environmental regulation on the rationalization of its industrial structure are shown in Table 7. According to the test results in Table 7, the *Sargan test* assumes that the overidentification constraints of each stepwise regression model are valid and that all instrumental variables are valid. The AR (1) statistic rejects the original assumption that the first-order sequence has no autocorrelation, but the AR (2) statistic accepts the original assumption that the second-order sequence has no autocorrelation, indicating that the model setting is reasonable. Next, we analyze the impact of China's environmental regulation on the rationalization of its industrial structure.

The (1) column in Table 7 shows the estimation results of the system without any control variables. The results show that the regression coefficient of the variable *ER* is significantly positive at the 1% level, indicating that environmental regulation has not promoted UIS. From columns (2) to (6), we have gradually introduced control variables such as economic development level, urbanization process, openness to the outside world, human capital level, and fiscal freedom. According to the results, the regression coefficient of the variable *ER* is still very significant, and the fluctuation range of the estimated coefficient is relatively small. On the one hand, this indicates that the various regression models set are not severely affected by multicollinearity issues, and the model settings are reasonable. On the other hand, this indicates that enhancing the intensity of environmental regulation is not conducive to UIS.

In terms of control variables, the estimated coefficient of the variable *Pgdp* is significantly negative at the 1% level, indicating that the higher the level of economic development, the more it can promote RIS. The higher the level of economic development, the more per capita disposable income there is and, thus, the demand for goods becomes more diverse, giving rise to new industries, bringing new economic growth points, and promoting the evolution of industrial structure. The estimated coefficient of the variable *Urban* is significantly positive, indicating that the urbanization process has a negative impact on RIS. A possible reason is that the development of urbanization in China is driven by production factors such as land, capital, and labor, and the total factor productivity is low, resulting in low quality of urbanization development. The urbanization process under the traditional

extensive economic growth model is not conducive to RIS. The estimated coefficient of the variable *Open* is significantly negative, indicating that a higher degree of openness to the outside world promotes RIS. The estimated coefficient of variable *Edu* is significantly negative, indicating that the higher the level of human capital, the more favorable it is to suppress the deviation of industrial structure from balanced development. In fact, the quantity, quality, and structure of human capital possessed by a country can determine its ability to adjust its industrial structure. Therefore, it is possible to promote RIS by improving the level of human capital. The estimated coefficient of the variable *Fiscal* is negative but not significant, indicating that the existing degree of fiscal freedom has played a small promoting role in industrial structure adjustment.

Table 7. Estimated results of the impact of environmental regulation on RIS.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
TL (−1)	0.2238 **	0.1698 ***	0.1603 ***	0.1572 ***	0.1509 **	0.1296 ***
	(2.20)	(4.55)	(3.14)	(2.73)	(2.20)	(3.07)
ER	0.1973 ***	0.1298 ***	0.1313 ***	0.1367 ***	0.1274 ***	0.1197 ***
	(7.94)	(8.95)	(13.92)	(12.03)	(10.67)	(8.16)
Pgdp		−0.1474 ***	−0.1649 ***	−0.1481 ***	−0.1278 ***	−0.0870 **
		(−19.96)	(−14.68)	(−6.49)	(−4.04)	(−2.19)
Urban			0.0724 **	0.2689 ***	0.4794 ***	0.4122 ***
			(2.08)	(3.06)	(3.07)	(4.57)
Open				−0.0267 ***	−0.0278 ***	−0.0269 ***
				(−7.70)	(−5.42)	(−8.76)
Edu					−0.0612 ***	−0.0550 ***
					(−4.45)	(−3.01)
Fiscal						−0.0831
						(−0.81)
Constant	0.0528	1.5800 ***	1.7279 ***	1.5335 ***	1.7838 ***	11.4075 ***
	(1.24)	(21.89)	(14.51)	(7.43)	(5.56)	(3.31)
AR (1)	−2.8703	−3.1880	−3.1727	−3.0742	−3.0351	−3.0714
	(0.0041)	(0.0014)	(0.0015)	(0.0021)	(0.0024)	(0.0021)
AR (2)	1.6023	1.4564	1.524	−0.3463	−1.518	−1.5172
	(0.1132)	(0.1471)	(0.1132)	(0.7291)	(0.1290)	(0.1221)
Sargan	11.9919	11.9742	11.9568	11.8629	11.8411	10.3314

Note: The values shown in parentheses are z values. The values in parentheses in the second row of AR (1) and AR (2) tests represent the probability of the corresponding statistic, with ***, ** representing significance at confidence levels of 1%, 5%, respectively.

5.2. Estimation Results of Impact of Environmental Regulation on UIS at the National Level

The estimated impact of environmental regulation on UIS is shown in Table 8. From the test results in Table 8, it can be seen that the *Sargan test* cannot reject the null hypothesis, i.e., that the instrumental variable is valid. Therefore, the system generalized moment estimation is valid. At the same time, the AR (1) statistic rejects the original assumption that first-order sequences have no autocorrelation, but the AR (2) statistic accepts the original assumption that second-order sequences have no autocorrelation, indicating that the model setting is reasonable. In addition, the estimation coefficient of the first-order lag term of the dependent variable *ES* in the model is significantly positive, indicating that there is significant inertia in industrial structure adjustment. The setting of the dynamic model in this article is, therefore, reasonable.

The (1) column in Table 8 shows the estimation results without any control variables. The regression coefficient of the variable *ER* is significantly positive at the 1% level, indicating that environmental regulation can promote UIS. From columns (2) to (6), we have gradually introduced control variables such as economic development level, urbanization process, openness to the outside world, human capital level, and fiscal freedom. It can be found that regardless of whether a control variable is added or not, the regression coefficient of the variable *ER* is still very significant. On the one hand, it indicates that

the various regression models set are severely affected by multicollinearity issues, and the model settings are reasonable. On the other hand, it indicates that enhancing the intensity of environmental regulation is beneficial for UIS.

Table 8. Estimated results of the impact of environmental regulation on UIS.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
ES (−1)	0.1367 *	0.0503 **	0.0305 *	0.0371 *	0.0278 **	0.0248 **
	(1.66)	(2.32)	(1.85)	(1.76)	(2.01)	(2.13)
ER	0.1114 ***	0.1630	0.2124 ***	0.2099 ***	0.2098 ***	0.2141 ***
	(6.12)	(6.65)	(9.44)	(8.40)	(8.60)	(8.26)
Pgdp		0.7959 ***	0.4689 ***	0.4655 ***	0.4934 ***	0.4439 ***
		(12.01)	(6.19)	(5.22)	(5.04)	(2.88)
Urban			1.3916 ***	1.5815 ***	1.5266 ***	1.5517 ***
			(6.20)	(5.14)	(4.19)	(4.06)
Open				−0.0124 **	−0.0138 *	−0.0166
				(−2.05)	(−1.92)	(−1.64)
Edu					0.0182 ***	0.0125 ***
					(3.24)	(3.01)
Fiscal						0.0881
						(0.48)
Constant	0.6996	−7.2602	−4.5981	−4.5829 ***	−4.7071 ***	−4.3253 ***
	(8.16)	(−11.26)	(6.60)	(−5.66)	(4.58)	(−3.08)
AR (1)	−3.0156	−3.1124	−3.2081	−3.1788	−3.1812	−3.2001
	(0.0026)	(0.0019)	(0.0013)	(0.0015)	(0.0015)	(0.0014)
AR (2)	−1.1013	0.3222	0.4132	1.2541	0.5612	1.4160
	(0.3106)	(0.7473)	(0.6125)	(0.4205)	(0.4892)	(0.1621)
Sargan	11.9253	11.6169	11.6025	11.5830	11.1837	10.8318

Note: Same as Table 7. ***, **, and * represent significant values at 1%, 5%, and 10% confidence levels, respectively.

Among other influencing factors, the higher the level of economic development, the more it can promote UIS. In areas with high levels of economic development, the factor endowment is dominant, and factors such as capital, labor, and management are fully utilized, providing a strong impetus for economic development, which is conducive to the rapid improvement of technology and industrial upgrading. The process of urbanization can significantly promote UIS and drive the upgrading of industrial structure. With the development of urbanization, the process of industrial agglomeration has been accelerated, and professional division of labor and an agglomeration economy have improved the level of production technology, thereby providing a strong driving force for industrial upgrading.

In addition, urban development attracts continuous population agglomeration, accelerating the accumulation of human capital and knowledge spillover, triggering technological innovation and promoting industrial upgrading. A high degree of opening up to the outside world is not conducive to UIS, possibly due to the fact that after a large influx of foreign investment into China, the vast majority enters the manufacturing industry, promoting the development of capital and technology in said industry, while less flows into the service industry. The higher the level of human capital, the more it can promote UIS. Human capital, as a carrier of technological progress, can trigger technological innovation through learning by doing and knowledge spillover, improving technology absorption and research and development efficiency. The accumulation of human capital has positive impacts on technological progress and the improvement of social productivity; therefore, increasing human capital is conducive to UIS. Regional fiscal freedom has a positive effect on UIS, but the results are not very significant.

5.3. Estimation Results of Impact of Environmental Regulation on RIS at the Regional Level

Due to China's vast territory and extremely uneven regional development, there are also significant differences in the environmental regulatory policies formulated by

different regions. Due to its geographical advantages the eastern region of China historically achieved industrialization earlier and developed its economy earlier and at a higher level of development. The legal system and environmental policy formulation are relatively complete, and correspondingly, the region faces strong environmental regulation. Due to relatively weak infrastructure and a lack of geographical advantages, the economic development level in the central and western regions of China is relatively low, and there exist industries that sacrifice the environment for the sake of economic growth. Therefore, the introduction of environmental policies in this region was relatively late, and the phenomenon of incomplete implementation of environmental regulatory policies is relatively common. There are significant differences in industrial development among different regions in China, resulting in industrial gradients. Therefore, there is significant regional heterogeneity in the impact of environmental regulation on the transformation and upgrading of industrial structure. In order to avoid biased conclusions, this article further divides the national sample into three major regions, namely eastern, central, and western regions, in order to study the regional heterogeneity of the impact of environmental regulation on the rationalization and elevation of industrial structure in each region.

Table 9 reports the estimated results of the impact of environmental regulation on RIS in the eastern, central, and western regions of China. Among them, columns (1) and (2) represent the estimated results for the eastern region, columns (3) and (4) represent the estimated results for the central region, and columns (5) and (6) represent the estimated results for the western region. According to the estimated results shown in the table, the estimated coefficients of environmental regulation variables in both the eastern and western regions are significantly positive at the 1% level, indicating that the implementation of environmental regulation is not conducive to RIS. The estimated coefficient of environmental regulation variables in the central region is significantly negative, indicating that environmental regulation has promoted RIS. From this, it can be seen that the effect of environmental regulation on RIS varies significantly in different regions of China: the eastern and western regions exhibit inhibitory effects, while the central region exhibits promoting effects.

Table 9. Regional estimation results of the impact of environmental regulation on RIS.

Variables	Eastern Region		Central Region		Western Region	
	(1)	(2)	(3)	(4)	(5)	(6)
TL (−1)	0.1966 *	0.2947 ***	10.0842 *	0.0344 *	0.1127 *	0.1968 **
	(1.68)	(3.39)	(1.73)	(1.82)	(1.89)	(2.15)
ER	0.1307 ***	0.1591 ***	−0.1518 ***	−0.0918 **	0.1476 ***	0.1625 ***
	(10.00)	(5.37)	(4.93)	(2.43)	(4.78)	(5.83)
Pgdp		−0.0963 *		−0.0927 **		−0.6072 ***
		(−1.83)		(−2.14)		(−2.68)
Urban		0.2849 ***		0.3741 **		0.6799
		(2.60)		(2.47)		(1.24)
Open		−0.0142 ***		−0.0695 ***		−0.1963 ***
		(−4.67)		(−2.94)		(−5.74)
Edu		−0.0645 **		−0.0304 ***		−0.0329
		(−2.59)		(3.14)		(0.95)
Fiscal		−0.0987		0.6542 **		0.6330 **
		(−1.01)		(2.08)		(2.18)
Constant	0.0377 **	1.4071 ***	0.3543 ***	0.6781 ***	0.2758 ***	0.5391 ***
	(2.39)	(4.74)	(11.88)	(5.27)	(4.37)	(3.28)
AR (1)	−2.5132	−2.7513	−2.5395	−2.1221	−2.4180	−2.3444
	(0.0120)	(0.0059)	(0.0111)	(0.0338)	(0.0156)	(0.0191)
AR (2)	−1.5029	1.5331	(−1.2381)	0.3119	−0.5741	−1.5736
	(0.1329)	(0.1253)	(0.2157	(0.7551)	(0.5659)	(0.1156)
Sargan	11.9795	11.9794	11.9846	9.1148	11.9138	9.4677

Note: Same as Table 7. ***, **, and * represent significant values at 1%, 5%, and 10% confidence levels, respectively.

For a long time, the eastern region has relied on its geographical advantages and policy preferences to achieve rapid economic development. There is no longer a need to sacrifice the environment for economic development. The demand for environmental governance is stronger, and the level of environmental regulation is higher. Pollution-intensive, high-energy-consumption, and low-end backward industries face high environmental cost pressure, shortening the life cycle of enterprises or motivating industries to transfer to areas with more relaxed environmental policies. The friction brought about by industrial changes has increased the cost of factor replacement, which is not conducive to the optimal allocation of resources among industries and inhibits RIS.

Compared with the eastern region of China, the country's central region presents another trend. The central region of China is densely populated, with fertile land and abundant natural resources. Transportation, communication, and energy infrastructure are becoming increasingly perfect, and the market environment, investment environment, and institutional environment have greatly improved. Low labor costs and abundant natural resources attract industrial transfer and production factor flow to the eastern region of China. Compared to local industries, eastern-transfer industries are technologically advanced and have higher production efficiency, which can further strengthen the correlation between industries and promote RIS.

The foundation of the western region of China is weak, economic development in the area historically started relatively late, the region's construction process is slow, and there is a lack of characteristic advantages in leading industries. Low-level repetitive construction leads to the convergence of industrial structure, a low degree of correlation between enterprises, poor collaboration ability, and failure to form a reasonable division of labor. Therefore, the formulation of environmental regulation policies has not effectively achieved coordinated development with the local economy, which is not conducive to RIS.

5.4. Estimation Results of Impact of Environmental Regulation on UIS at the Regional Level

Table 10 reports the estimated results of the impact of environmental regulation on UIS in the eastern, central, and western regions of China. Columns (1) and (2) represent the estimated results for the eastern region, columns (3) and (4) represent the estimated results for the central region, and columns (5) and (6) represent the estimated results for the western region. Furthermore, this article examines the regionally heterogeneous impact of China's environmental regulation on its UIS. According to the estimated results in Table 10, the estimated coefficients of environmental regulation in the eastern and western regions of China are significantly positive at the 1% level, indicating that environmental regulation can significantly drive UIS. The estimated coefficient of environmental regulation in the central region of China is significantly negative, indicating that environmental regulation is not conducive to promoting UIS in the region but rather suppresses UIS.

A possible explanation for this is that the eastern region has experienced an early economic takeoff, rapid economic development, a high degree of marketization, and a strong willingness for enterprises to pursue high profits and defeat competitors. Historically, the government in this region introduced a series of environmental protection policies, regulations, and laws earlier and promoted the sound and healthy operation of institutional mechanisms. The higher intensity of environmental regulation increases the cost of pollution control for polluting enterprises, forcing pollution-intensive industries to migrate to areas with higher levels of environmental regulation tolerance or increasing innovative investment in green and clean technologies to reduce pollution costs. At the same time, with the improvement of environmental regulation intensity, highly polluting enterprises are gradually being phased out, and the remaining enterprises have high market competitiveness and attach more importance to scientific research and innovation capabilities, thereby promoting UIS.

The central region of China is rich in resources and densely populated. In the process of development, there is a high demand for investment attraction and it is easy to fall into the dilemma of pollution shelters. In addition, the central region has weak basic

innovation capabilities and high innovation costs, making it easier to seek end-of-life pollution control methods when facing the pressure of tightening environmental protection. The increase in pollution control costs has squeezed the profit space of enterprises, which is not conducive to increasing technological innovation investment, making it difficult to improve associated technological levels, further hindering the green innovation and product upgrading of enterprises. The implementation of environmental regulation is not conducive to promoting UIS in the region.

Table 10. Regional estimation results of the impact of environmental regulation on UIS.

Variables	Eastern Region		Central Region		Western Region	
	(1)	(2)	(3)	(4)	(5)	(6)
ES (−1)	0.0196 *	0.0216 **	0.3157 **	0.2014 **	0.0866 *	0.0486 **
	(1.78)	(2.32)	(2.27)	(2.43)	(1.75)	(2.41)
ER	0.2741 ***	0.2115 ***	−0.5165 ***	−0.5164 ***	0.0925 ***	0.1996 ***
	(12.01)	(10.21)	(−3.08)	(3.94)	(5.16)	(5.75)
Pgdp		0.0153 **		0.6440 ***		0.7521 ***
		(2.11)		(5.41)		(3.64)
Urban		0.3657 ***		0.2154 ***		0.5655
		(3.43)		(4.23)		(4.21)
Open		0.0203 **		0.1199 ***		−0.3389 ***
		(2.54)		(3.78)		(−7.00)
Edu		0.3486		0.0566 *		0.2128 ***
		(8.63)		78)		(3.14)
Fiscal		1.6224 ***		0.4549		0.7764 *
		(6.71)		(0.5)		(1.92)
Constant	1.1603	11.2507 ***	0.6485 ***	5.3939	0.5259 ***	2.3049 *
	(15.5)	(3.49)	(4.00)	(7.29)	(4.23)	(1.76)
AR (1)	−2.2116	−3.0093	−1.9567	−1.8729	−2.1356	−3.0223
	(0.0270)	(0.0026)	(0.0504)	(0.0312)	(0.0327)	(0.0025)
AR (2)	−1.5213	0.7645	−0.2794	−0.6972	−1.4125	−0.9414
	(0.1421)	(0.4445)	(0.7799)	(0.4857)	(0.1365)	(0.3465)
Sargan	11.7946	6.9449	11.9647	0.8907	11.9505	7.6565

Note: Same as Table 7. ***, **, and * represent significant values at 1%, 5%, and 10% confidence levels, respectively.

The western region of China is at a disadvantage in terms of geographical location, environment, and education. The region's economy started relatively late and developed slowly. For a long time, agriculture and animal husbandry have occupied the main position in its economic development, with low-end core industries and a lack of high-tech industries willing to play a leading role in promoting economic development. In order to aid in the economic development of the western region, the Western Development Strategy proposed in 2000 aims to improve the economic and social development level of the western region of China. The release of policy dividends has gradually promoted the coordination of economic development with population, resources, and the environment in the western region, promoting the improvement of its ecological environment, business environment, and innovation environment. Environmental regulation can stimulate the innovation compensation effect in the region and ultimately promote its UIS.

5.5. Robust Test

In order to verify the robustness of the above findings on the impact of China's environmental regulation on the transformation and upgrading of industrial structure, the ratio of pollution discharge fee income to the industrial added value in each region was further used as a substitute to regress the model. The results of robustness regression are shown in Table 11. To save space, Table 11 does not provide regression results for the control variables. Compared with the above regression results, the size of the coefficient of environmental regulatory variables has changed, but the significance and direction have not changed, which better proves the robustness of the above research conclusions.

Table 11. Robustness test results.

Variables	Eastern Region		Central Region		Western Region	
	TL	***ES***	***TL***	***ES***	***TL***	***ES***
ES (−1)/*TL* (−1)	0.3236 ***	0.0275 **	0.0416 **	0.1843 **	0.1853 **	0.0501 **
	(3.41)	(2.47)	(2.36)	(2.52)	(2.24)	(2.38)
ER	0.1732 ***	0.2538 ***	−0.0724 **	−0.4053 ***	0.1431 ***	0.2163 ***
	(4.52)	(7.33)	(2.18)	(3.49)	(4.13)	(6.05)
Constant	1.6202 ***	9.1532 ***	0.7262 ***	3.1634 ***	1.2644 ***	2.1532 ***
	(4.94)	(4.16)	(3.71)	(5.09)	(3.53)	(4.82)
AR (1)	−2.5117	−3.0184	−2.2645	−1.6562	−2.1043	−3.1349
	(0.0048)	(0.0032)	(0.0247)	(0.0402)	(0.0238)	(0.0036)
AR (2)	1.6216	0.5835	0.3536	−0.5874	−1.4483	−0.7264
	(0.1308)	(0.3275)	(0.6211)	(0.4163)	(0.1742)	(0.3537)
Sargan	10.8592	6.2446	8.4262	8.9173	8..2 167	7.3174

Note: Same as Table 7.

6. Conclusions and Policy Recommendations

Realizing sustainable economic development is an important goal pursued by policy authorities, and the transformation and upgrading of industrial structure constitute a necessary means to achieving sustainable development. Therefore, it is particularly important to examine those factors promoting industrial upgrading. Previous research findings have confirmed that traditional tools such as financial instruments and fiscal policies have a significant impact on industrial structure upgrading. However, due to the current constraints of insufficient policy space, the policy implementation of these tools is greatly limited. Therefore, we recommend shifting the focus of research to environmental policies as effective supplements to traditional tools, delving into their impact on industrial structure, in order to compensate for the ineffectiveness of traditional policies and inject new policy momentum into sustainable economic development.

This article analyzes the correlation between China's environmental regulation and the transformation and upgrading of its industrial structure. Environmental regulation has a significant impact on RIS and UIS. Based on the correlation between environmental regulation and industrial structure transformation and upgrading, we established a dynamic panel model and analyzed the impact of China's environmental regulation on its industrial structure transformation and upgrading. In addition, considering the extremely uneven development of China's regions and the significant differences in environmental regulation policies formulated by different regions, the national sample is further divided into three major regions, namely eastern, central, and western regions, in order to study the regional heterogeneity of the impact of environmental regulation on RIS and UIS in each region. The main conclusions drawn in this article are as follows:

(1) This article establishes a PVAR model to explore the correlation between environmental regulation and the transformation and upgrading of industrial structure. According to presented impulse response curves, it can be seen that the impact of environmental regulation on RIS and UIS is very significant. Specifically, the impact of environmental regulation has a positive impact on RIS, while the impact on UIS is relatively complex, initially having a negative impact followed by a positive impact and, in the long run, the degree of impact decreases and stabilizes. We also analyzed the impact of environmental regulation on RIS and UIS through variance decomposition. Fluctuations in environmental regulation can explain 37.75% of changes in RIS, and the fluctuation of environmental regulation can explain 23.5% of changes in UIS;

(2) Overall, by controlling variables such as economic development level, urbanization process, openness to the outside world, human capital level, and fiscal freedom, it is found that strengthening the level of environmental regulation is not conducive to RIS, but a strong level of environmental regulation can significantly promote UIS. Variables such as economic development level and human capital level promote RIS and UIS. Urbanization is not conducive to RIS, but it promotes UIS. The degree of

openness to the outside world is conducive to RIS but not conducive to UIS. The impact of fiscal freedom on RIS and UIS is not significant.

(3) At the regional level, there is significant regional heterogeneity in the impact of China's environmental regulations on the transformation and upgrading of industrial structures in different regions. Environmental regulatory policies can promote UIS in the eastern and western regions of China but are not conducive to RIS. For the central region of China, environmental regulations promote RIS but have a negative impact on UIS. A possible reason for this is that the demand for environmental governance in the eastern region of China is stronger due to advantages associated with its location, which promotes UIS. However, the friction brought about by industrial changes has increased the cost of factor replacement, which is not conducive to the optimal allocation of resources among industries and inhibits RIS. The technology of eastern-transfer industries from the central region is perfect, which promotes RIS, but the central region's basic innovation ability is weak, which is not conducive to UIS.

Based on the above research conclusions, this article proposes the following policy recommendations: (1) The government should fully explore and leverage the positive role of environmental regulation in industrial structure transformation. It is also necessary to pay attention to the impact of environmental regulation on the transformation and upgrading of local industrial structures. Properly increasing the intensity of environmental regulation can help improve the ecological environment and promote the upgrading of industrial structure. The government should consider the carrying capacity of economic entities when formulating environmental regulation policies and gradually adjust the intensity of environmental regulation to avoid generating excessive environmental costs that inhibit the innovation enthusiasm of enterprises. (2) China's regional development is imbalanced, and there are significant differences in environmental regulation levels among different regions. A one-size-fits-all environmental policy cannot meet the environmental governance needs of different regions. The government's formulation of environmental regulation policies needs to combine regional characteristics, pay attention to the regional heterogeneity of environmental regulation's impact on industrial structure transformation and upgrading, and formulate differentiated environmental protection policies tailored to local conditions. (3) In the mechanism path of environmental regulation affecting industrial structure transformation and upgrading, full leverage of the positive role of human capital should be utilized in industrial transformation and upgrading. Relevant departments should strengthen the introduction of high-tech human capital, establish diversified talent introduction mechanisms, and attract high-level human resource clusters through generous material rewards and spiritual incentives, which can help promote the process of industrial structure transformation and upgrading.

Finally, it should be pointed out that this study is an empirical analysis based on provincial panel data and does not include industry factors in its scope. Due to differences in policy orientation, energy dependence, and pollution emissions, the impact of environmental regulation on industrial structure will vary in different industries. Therefore, when formulating and implementing environmental regulation policies, not only regional differences but also industry characteristics should be taken into account. In addition, the types of environmental regulation can be divided into command-and-control types, economic incentive types, and voluntary types. The indicators selected in this paper only consider the intensity of command-and-control environmental regulation, without examining the industrial adjustment effects of other types of environmental regulation. This is also the direction and focus of our future research.

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References

1. Lin, X.; Guan, S. Do environmental regulations Promote the transformation and upgrading of industrial structure?—A strategic interaction perspective based on the implementation of local government environmental regulations. *South Econ.* **2020**, *11*, 99–115.
2. Guan, S.; Liu, J.; Liu, Y.; Du, M. The nonlinear influence of environmental regulation on the transformation and upgrading of industrial structure. *Int. J. Environ. Res. Public Health* **2022**, *19*, 8378. [CrossRef] [PubMed]
3. Ambec, S.; Barla, P. A theoretical foundation of the Porter hypothesis. *Econ. Lett.* **2002**, *75*, 355–360. [CrossRef]
4. Song, Y.; Ma, J.; Guan, S.; Liu, Y. Fiscal Decentralization, Regional Innovation and Industrial Structure Distortions in China. *Sustainability* **2022**, *15*, 710. [CrossRef]
5. Li, Z.; Huang, Z.; Su, Y. New media environment, environmental regulation and corporate green technology innovation: Evidence from China. *Energy Econ.* **2023**, *119*, 106545. [CrossRef]
6. Lin, X.; Guan, S. The nonlinear impact of environmental regulation on manufacturing upgrading in China: An empirical analysis based on panel smooth migration model. *J. Xi'an Jiaotong Univ. Soc. Sci. Ed.* **2019**, *39*, 1–8.
7. Yang, X.; Jiang, P.; Pan, Y. Does China's carbon emission trading policy have an employment double dividend and a Porter effect? *Energy Policy* **2020**, *142*, 111492. [CrossRef]
8. Eskeland, G.S.; Harrison, A.E. Moving to greener pastures? Multinationals and the pollution haven hypothesis. *J. Dev. Econ.* **2003**, *70*, 1–23. [CrossRef]
9. Lodi, C.; Bertarelli, S. Eco-innovation and exports in heterogeneous firms: Pollution haven effect and porter hypothesis as competing theories. *Econ. Innov. New Technol.* **2023**, *32*, 923–952. [CrossRef]
10. Wang, X.; Zhang, C.; Zhang, Z. Pollution haven or porter? The impact of environmental regulation on location choices of pollution-intensive firms in China. *J. Environ. Manag.* **2019**, *248*, 109248. [CrossRef]
11. Dou, J.; Han, X. How does the industry mobility affect pollution industry transfer in China: Empirical test on Pollution Haven Hypothesis and Porter Hypothesis. *J. Clean. Prod.* **2019**, *217*, 105–115. [CrossRef]
12. Marconi, D. Environmental regulation and revealed comparative advantages in Europe: Is China a pollution haven? *Rev. Int. Econ.* **2012**, *20*, 616–635. [CrossRef]
13. Zheng, D.; Shi, M. Multiple environmental policies and pollution haven hypothesis: Evidence from China's polluting industries. *J. Clean. Prod.* **2017**, *141*, 295–304. [CrossRef]
14. Taylor, M.S. Unbundling the pollution haven hypothesis. *Adv. Econ. Anal. Policy* **2005**, *4*. [CrossRef]
15. Solarin, S.A.; Al-Mulali, U.; Musah, I. Investigating the pollution haven hypothesis in Ghana: An empirical investigation. *Energy* **2017**, *124*, 706–719. [CrossRef]
16. Gill, F.L.; Viswanathan, K.K.; Karim, M.Z.A. The critical review of the pollution haven hypothesis. *Int. J. Energy Econ. Policy* **2018**, *8*, 167–174.
17. Wagner, U.J.; Timmins, C.D. Agglomeration effects in foreign direct investment and the pollution haven hypothesis. *Environ. Resour. Econ.* **2009**, *43*, 231–256. [CrossRef]
18. Kearsley, A.; Riddel, M. A further inquiry into the pollution haven hypothesis and the environmental Kuznets curve. *Ecol. Econ.* **2010**, *69*, 905–919. [CrossRef]
19. Singhania, M.; Saini, N. Demystifying pollution haven hypothesis: Role of FDI. *J. Bus. Res.* **2021**, *123*, 516–528. [CrossRef]
20. Sanchez-Vargas, A.; Mansilla-Sanchez, R.; Aguilar-Ibarra, A. An empirical analysis of the nonlinear relationship between environmental regulation and manufacturing productivity. *J. Appl. Econ.* **2013**, *16*, 357–371. [CrossRef]
21. Liu, Y.; Luo, N.; Wu, S. Nonlinear effects of environmental regulation on environmental pollution. *Discret. Dyn. Nat. Soc.* **2019**, *2019*, 6065396. [CrossRef]
22. Yang, G.; Zha, D.; Wang, X. Exploring the nonlinear association between environmental regulation and carbon intensity in China: The mediating effect of green technology. *Ecol. Indic.* **2020**, *114*, 106309. [CrossRef]

23. Chen, J.; Hu, L. Does environmental regulation drive economic growth through technological innovation: Application of nonlinear and spatial spillover effect. *Sustainability* **2022**, *14*, 16455. [CrossRef]
24. Chen, X.; Chen, Y.E.; Chang, C.P. The effects of environmental regulation and industrial structure on carbon dioxide emission: A non-linear investigation. *Environ. Sci. Pollut. Res.* **2019**, *26*, 30252–30267. [CrossRef] [PubMed]
25. Chen, L.; Li, W.; Yuan, K. Can informal environmental regulation promote industrial structure upgrading? Evidence from China. *Appl. Econ.* **2022**, *54*, 2161–2180. [CrossRef]
26. Gereffi, G. International trade and industrial upgrading in the apparel commodity chain. *J. Int. Econ.* **1999**, *48*, 37–70. [CrossRef]
27. Azadegan, A.; Wagner, S.M. Industrial upgrading, exploitative innovations and explorative innovations. *Int. J. Prod. Econ.* **2011**, *130*, 54–65. [CrossRef]
28. Cheong, T.S.; Wu, Y. The impacts of structural transformation and industrial upgrading on regional inequality in China. *China. Econ. Rev.* **2014**, *31*, 339–350. [CrossRef]
29. Du, K.; Cheng, Y.; Yao, X. Environmental regulation, green technology innovation, and industrial structure upgrading: The road to the green transformation of Chinese cities. *Energy Econ.* **2021**, *98*, 105247. [CrossRef]
30. Wei, H.; Yao, H. Environmental regulation, roundabout production, and industrial structure transformation and upgrading: Evidence from China. *Sustainability* **2022**, *14*, 3810. [CrossRef]
31. Hu, H.; Liu, C. Can technology finance policies promote the transformation and upgrading of industrial structure? *Stud. Int. Financ.* **2021**, *5*, 24–33.
32. Wang, C.; Zhu, R. Monetary policy and financial market effects in industrial structure upgrading: Analysis based on BVAR model and threshold regression model. *Financ. Econ.* **2016**, *4*, 23–34.
33. Liu, Z.; Liu, X.; Wang, L. Policy coordination, industrial structure upgrading, and macroeconomic effects analysis. *Commer. Res.* **2020**, *4*, 56–67.
34. Yu, B. The economic growth effect of industrial structure adjustment and productivity improvement: An analysis based on the dynamic spatial panel model of Chinese cities. *China Ind. Econ.* **2015**, *12*, 83–98.
35. Gan, C.; Zheng, R.; Yu, D. The Impact of Industrial Structure Change on Economic Growth and fluctuation in China. *Econ. Res.* **2011**, *46*, 4–16.
36. Yuan, H.; Zhu, C. Do National high-tech Zones promote the transformation and upgrading of China's industrial structure. *China Ind. Econ.* **2018**, *8*, 60–77.
37. Liu, W.; Zhang, H.; Huang, Z. Study on the height of industrial structure, industrialization process and regional differences in China. *J. Econ.* **2008**, *11*, 4–8.
38. Jian, X.; Ye, L. Empirical analysis on the evolution and optimization of China's industrial structure since the reform and opening up. *Contemp. Financ. Econ.* **2011**, *1*, 93–102.
39. Du, L. Influencing factors of carbon dioxide emission in China: A study based on provincial panel data. *South Econ.* **2010**, *11*, 20–33.
40. Arellano, M.; Bond, S. Some tests of specification for panel data: Monte Carlo evidence and an application to employment equations. *Rev. Econ. Stud.* **1991**, *58*, 277–297. [CrossRef]
41. Blundell, R.; Bond, S. Initial conditions and moment restrictions in dynamic panel data models. *J. Econ.* **1998**, *87*, 115–143. [CrossRef]
42. Jin, G.; Shen, K. Beggar thy neighbor or partner thy neighbor?—Interaction of environmental regulation enforcement and urban productivity growth. *Manag. World* **2018**, *34*, 43–55.

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