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Oz Sahin and Russell Richards

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Editorial

Sustainable Development of Energy, Water and Environment Systems (SDEWES2024)

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1. Introduction

Since the first conference on the Sustainable Development of Energy, Water, and Environment Systems (SDEWES) was held in Dubrovnik in 2002, this conference series has been providing a global forum for scientists and other stakeholders interested in sustainability to share their research and contribute towards meeting the grand challenges that we face both in the present and the future. An important part has been enabling this state-of-the-art, multi-disciplinary research to be communicated so that it can contribute towards the discussion around future directions and priorities in sustainable development.

Sustainability has emerged as a defining grand challenge of the 21st century, encompassing environmental, economic, technological, political, and social concerns. The ten studies that comprise this Special Issue reflect the diversity and complexity of sustainability research, each contributing distinct insights into how societies, systems, and technologies can evolve toward more resilient and equitable futures. While the thematic scope of these papers is broad (e.g., built environment, energy systems, agriculture, artificial intelligence, and circularity), they together share a commitment to advancing sustainability research.

At its core, sustainability is a systems concept, concerned not only with resource efficiency and environmental stewardship but also with the interdependencies between human well-being, economic performance, technological progress, and governance. Several papers in this collection emphasise the importance of systemic thinking (contribution 1; contribution 8) and/or interdisciplinary (contribution 2; contribution 8) research. All papers addressed the importance of the economic dimension, and almost all addressed the political dimension, highlighting the importance of the 'political economy' in sustainability (e.g., contribution 2).

Various sub-themes emerged from the articles including the integration of digital technologies, especially in the context of agriculture (contribution 2; contribution 8; contribution 10) and 'circularity' (contribution 4; contribution 6; contribution 7). These efforts reflect a growing recognition that sustainability is not merely about minimising harm but about rethinking production and consumption systems to enable long-term regeneration. Unsurprisingly, artificial intelligence (AI) emerged as a potential enabler, including in construction to predict microstructural changes in materials (contribution 9), and in agriculture for supporting precision farming (contribution 2). However, the deployment of AI also raises ethical and governance questions, particularly around data privacy, security and equity, and this will undoubtedly become a rich area for future sustainable development research.

Finally, the theme of policy, equity, and governance runs throughout the collection. There is a general theme within many of these articles that advocate (or at least allude to this) for participatory, transparent, and context-sensitive approaches to sustainability. They highlight the need for policies that not only incentivise innovation but also safeguard social justice and environmental ethics.

In summary, these ten papers offer a rich tapestry of sustainability research, weaving together diverse methodologies, disciplines, locations, and perspectives. They demonstrate that sustainability is not a singular goal but a multidimensional process, one that requires collaboration across sectors, integration of technologies with values, and continuous reflection on the systems we inhabit and shape.

2. Sustainability in the Built Environment

The built environment is a critical frontier in the pursuit of sustainability, given its substantial contributions to global energy consumption, greenhouse gas emissions, and resource use. Within this domain, several articles offered perspectives on how planning, construction practices, material selection, and energy systems can be reimagined to support climate-neutral development.

Ferrante et al. (contribution 6) examined the role of Green Building Rating Systems in facilitating the transition to Positive Energy Districts (PEDs) whilst Del-Busto et al., (contribution 5) demonstrated how temporary street experiments could reconfigure urban public spaces to promote active mobility, reduce car dependency, and enhance environmental quality. Several papers focused on transformative approaches: Several addressed the issue at a 'large' scale. For example, Yin et al. (contribution 10) analysed how agricultural infrastructure and resource planning in Heilongjiang Province could be optimised to support sustainable development whilst Calcagni and Battisti (contribution 3) examined floating urban development (FUD) as a sustainable solution for climate-threatened coastal zones in Italy. This latter paper emphasising integration with energy systems like solar and wind while considering environmental and social impacts. Alongside this, Patel et al., (contribution 8) discussed the transformation of degraded peatlands into multifunctional landscapes. Meanwhile, Rudenko et al. (contribution 9) explored the potential of non-autoclaved aerated concrete (NAAC) enhanced with ash-and-slag waste (ASW) as a sustainable construction material, whilst Gasik-Kowalska and Koper (contribution 7) demonstrated how recycled ceramic waste could be used to reduce resource extraction and supporting energy-efficient construction practices. These studies converge on the principle that sustainability in the built environment requires a holistic approach, emphasising the need for policy frameworks that incentivise sustainable procurement and certification (contribution 6) and the role of innovation (contribution 9).

3. Agriculture and the Nexus of Technology and Values

Agriculture is undergoing a profound transformation, driven by digital technologies and shaped by evolving societal values. The concept of Agriculture 5.0, as addressed by Bergier et al. (contribution 2) encapsulates this shift, moving beyond the data-centric focus of Agriculture 4.0 to embrace a value-oriented framework that integrates technological innovation with socio-environmental sustainability.

Patel et al. (contribution 8) examined how peatland degradation from agricultural land use can be mitigated through restoration strategies, supported by technological interventions such as drainage control and remote sensing for monitoring ecosystem recovery. They found that this can significantly contribute to climate mitigation, biodiversity conservation, and resilient energy and agricultural systems, but importantly, success depends on integrated policy, technological innovation, and stakeholder collaboration.

Yin et al. (contribution 10) applied advanced machine learning and optimisation techniques to evaluate agricultural sustainability in Heilongjiang Province. While the focus was primarily technological, it supported sustainability values such as resource conservation, environmental protection, and equitable development through data-driven planning and system coordination. The future of agriculture lies in its ability to integrate cutting-edge technologies with deep cultural and ethical insights. By mapping the semantic landscape of sustainability and constructing a value-oriented framework.

Finally, Bergier et al. (contribution 2) provided a compelling vision for how agriculture can evolve to meet the demands of a complex, interconnected world. Their work serves as a model for how research can illuminate the pathways toward a more just, resilient, and sustainable food system.

4. Circularity

Circularity, which is the principle of designing systems that regenerate resources and minimise waste, is increasingly recognised as a foundational pillar of sustainability. Within the ten studies, circularity emerges not only as a material strategy but also as a conceptual and policy-oriented framework that intersects with construction, agriculture, and education. In the built environment, circularity is evident in the reuse and valorisation of industrial by-products. Carrasco and May (contribution 4) analysed life cycle and circular economy aspects of photovoltaic modules and lithium-ion batteries to increase the efficiency of used material at the design. Rudenko et al. (contribution 9) demonstrated how a by-product of coal combustion can be repurposed into non-autoclaved aerated concrete. In a similar vein, Gasik-Kowalska and Koper (contribution 7) showcased how recycled ceramic waste can be repurposed into durable concrete, reducing environmental impact and resource consumption in the construction sector. Ferrante et al. (contribution 6) extended the concept of circularity to the district scale through their analysis of Positive Energy Districts. By integrating green building rating systems, the authors showed how material selection criteria (recycled content, local sourcing, and life cycle assessment) can promote circular construction practices. In agriculture, circularity is embedded in the design of integrated systems that recycle nutrients, biomass, and knowledge. Bergier et al. (contribution 2) discussed how crop–livestock–forestry systems and agroforestry models can transform degraded lands into productive landscapes while maintaining ecological balance. These systems exemplify circularity by fostering synergies between different components of the agricultural ecosystem, such as using livestock manure to enrich soils or integrating tree cover to enhance biodiversity and carbon sequestration. Finally, circularity was also shown to intersect with education and policy with Abina et al. (contribution 1) highlighting how digital learning tools could support circular competency development by enabling learners to reflect on their skills, interests, and career trajectories. Similarly, Ferrante et al. (contribution 6) argued that policy frameworks such as Green Public Procurement and Minimum Environmental Criteria can institutionalise circularity by embedding it into procurement and certification processes.

5. Artificial Intelligence

Artificial Intelligence (AI) is increasingly recognised as a transformative force in sustainability research and practice. AI emerges not only as a tool for optimisation and prediction but also as a catalyst for rethinking how knowledge is generated, decisions are made, and systems are governed. From construction materials and agriculture to education and semantic data systems, AI is deployed in diverse contexts to enhance efficiency, precision, and adaptability while also raising critical questions about ethics, equity, and epistemology. In the domain of sustainable construction, Rudenko et al. (contribution 9) demonstrated how convolutional neural networks can be used to predict microstructural changes in non-autoclaved aerated concrete enhanced with ash-and-slag waste. By training neural models on chemical composition and physical parameters, the study achieved high accuracy in forecasting material performance, thereby supporting the industrial-scale application of low-impact building materials. This use of AI exemplifies how machine learning can contribute to circularity and resilience in the built environment by optimising resource use and reducing waste.

In agriculture, AI plays a central role in the transition from Agriculture 4.0 to Agriculture 5.0. Bergier et al. (contribution 2) mapped the semantic landscape of sustainability concepts using bipartite network analysis, revealing how high-centrality keywords such as "deep learning," "remote sensing," and "precision agriculture" dominate the technological discourse. Yin et al. (contribution 10) applied machine learning techniques to evaluate agricultural sustainability using an enhanced Random Forest model to analyse complex interactions in water-land-energy systems. AI was also highlighted as supporting personalised learning and competency development (contribution 1) whilst Del-Busto et al. (contribution 5) discussed AI as a tool for urban mobility monitoring.

Overall, AI was shown to be a powerful enabler of sustainability, offering tools for optimisation, prediction, and personalisation across multiple domains. However, it was also highlighted that its effectiveness depends on how it is embedded within broader systems of values, governance, and inclusion. The studies advocated for a balanced approach one that harnesses the capabilities of AI while remaining attentive to its limitations and ethical implications.

6. Policy, Equity and Governance

Sustainability is fundamentally shaped by the structures of policy, equity, and governance that determine how resources, knowledge, and opportunities are distributed. Across the ten studies in this Special Issue, these themes emerge as critical enablers and constraints. Whether through certification systems, youth empowerment, or cultural recognition, the governance of sustainability is shown to be deeply intertwined with questions of justice, participation, and institutional design.

The study by Del-Busto et al. (contribution 5) used street experiments to inform urban policy shifts, promote spatial justice and accessibility for vulnerable users, and foster participatory governance through collaborative evaluation frameworks with city stakeholders. Patel et al., (contribution 8) analysed how EU and national frameworks were guiding peatland restoration, emphasising the need for coordinated governance and equitable strategies that balance ecological goals with socioeconomic realities. Calcagni and Battisti (contribution 3) emphasised the importance of public engagement, regulatory compliance, and adaptive management in floating urban development, whilst also highlighting equity concerns, warning that without inclusive planning, such developments risk becoming exclusive luxury enclaves rather than accessible, socially integrated urban solutions. Yin et al. (contribution 10) highlighted the role of government policies in shaping water, land, and energy resource management and advocating for coordinated planning and regulation whilst also discussing regional disparities in resource capacity and the need for interdepartmental collaboration and data-driven governance to support equitable and sustainable agricultural development. Ferrante et al. (contribution 6) provide a compelling example of how policy frameworks can institutionalise sustainability in the built environment.

Bergier et al. (contribution 2) extended the discussion of governance into the domain of agriculture, where they argue for a value-oriented framework that integrates both material and immaterial assets. In the context of education and youth development, Abina et al. (contribution 1) explored how digital tools can support equitable access to sustainability competencies, demonstrating how governance can be enacted through designs that are accessible, responsive, and attuned to diverse learner needs.

Across these studies, governance is shown to be both a structural and a relational process. It involves the creation of standards, the design of platforms, and the negotiation of values. In summary, policy, equity, and governance are not peripheral concerns in sustainability, they are central to its realisation. The articles in this Special Issue demonstrate that sustainable transitions require more than technical solutions; they demand institutional innovation, cultural recognition, and ethical reflection.

7. Summary and Conclusions

Overall, the ten articles synthesised in this Editorial collectively show the multifaceted nature of sustainability, offering insights that span the built environment, digital education, agriculture, circularity, artificial intelligence, and governance. While each paper addresses distinct challenges and contexts, they are unified by a shared commitment to systemic thinking, innovation, and inclusivity. Together, these studies advocate for a sustainability agenda that is not only technically robust but also socially just and culturally attuned. The synthesis presented here underscores the importance of integrating diverse perspectives and methodologies in sustainability research. It calls for a future in which technology is guided by values, systems are designed for regeneration, and governance is rooted in equity.

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

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Article

Street Experiments Across EU Cities: An Exploratory Study on Leveraging Data for Urban Mobility Impact Evaluation †

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† This article is a revised and expanded version of a paper entitled 'Design and Testing of a Portable Laboratory for Evaluating the Effect of Local Urban Mobility Interventions'. In Proceedings of the 19th Conference on Sustainable Development of Energy Water and Environmental Systems, Rome, Italy, 8–12 September 2024.

Abstract: European cities are under pressure to be at the forefront of climate neutrality while providing inclusive, safe, and sustainable urban mobility. Street experiments are being adopted to accelerate this transition, yet assessing their impact remains challenging. This study addresses this gap by providing an evidence-based impact assessment of street experiments. The research builds on insights from 20 European cities, including 13 from the EU Cities Mission, regarding expected goals and current evaluation barriers. A preliminary quasi-experimental spatial and temporal approach is proposed and further enriched through the identification of the most relevant mobility domains and indicators addressed by cities. An exploration of data collection technologies is undertaken to meet the cities' needs, culminating in the design of a portable and easy-to-install laboratory, the Labkit, for in situ and non-intrusive evaluation of public space interventions. The Labkit is tested and validated in an open area with a constant flow of pedestrians, cyclists, e-scooters, and vehicles. The results of this testing process, along with feedback from cities regarding the methodological approach and potential indicators, are analysed. The study concludes with a discussion of the opportunities and limitations of data-driven approaches for urban mobility impact assessment and the proposal of future research directions.

Keywords: street experiments; impact evaluation; urban mobility indicators; data-driven assessment

1. Introduction

Sustainable mobility is essential to achieving climate neutrality, overcoming social inequalities [1], and fostering a competitive and resource-efficient transport system [2]. Beyond the efficient movement of people and goods, the discussion around transport has shifted towards addressing broader issues, such as global and local environmental effects and the wider social implications for health and inequality [3,4], among others. Urban planners and transport policymakers deal with complex urban dynamics that fluctuate from the vastness of regions to the bustling activities of streets. This requires a continuous evaluation, not only for the planning and implementation of mobility solutions but also for the subsequent impact assessment. Beneficial mobility interventions should be promoted and replicated based on evidence to increase public support [5]. Building on previous progress by the authors regarding the availability and pilot testing of market-ready data collection technologies for public space monitoring [6], this paper expands the insights into the impact evaluation of temporary pilot projects known as street experiments (SEs) [7].

On a global scale, cities must meet the challenges of the current climate crisis [8]. Transport is a key sector in achieving climate neutrality targets due to the difficulty of decoupling its contribution to economic development from its environmental impact [9].

In response to this challenge, the European Union (EU) Mission on Climate Neutral and Smart Cities, also known as the Cities Mission, was launched to support and promote 100 cities in their systemic transformation towards climate neutrality by 2030 [10]. In terms of decarbonisation, the Cities Mission applicants, representing 18% of the EU population, are mainly focusing on technological solutions, such as electrification, which may not be sufficient if mobility levels remain unchanged [11], if the externalities of electric vehicles are neglected [12], or if benefits are undermined by the so-called rebound effect [13,14].

Beyond its climate change contribution, urban transport generates various externalities that negatively impact mobility systems. The most critical ones are the invasion of public space for road construction, local air pollution, road accidents, congestion, vibration, and oil dependency, followed by barrier effects, noise, and visual blight [15]. Dependence on individual modes of transport has also led to sedentary lifestyles and a polluted environment, which affect people's physical and mental health [16,17]. The promotion of active mobility and public transport appears as a synergistic strategy to reduce pollution and congestion, increase safety and accessibility, improve the mental well-being of citizens, and even generate savings for society. These benefits are seen as equally positive by people from different backgrounds [18]. Even if there is initial public resistance to traffic restrictions, adopting sustainable mobility approaches enables a positive economic feedback loop with local businesses [19].

In this sense, current approaches to street design focus on the 'fair' distribution of public space, generally seeking to rebalance space between motorised and non-motorised transport and even between transport and other uses of public space [20–22]. Cities increasingly serve as testing grounds for SEs, a distinct type of pilot project that temporarily alters the use, regulation, design, or function of specific street sections, entire streets, or even larger urban areas. SEs offer a faster and cheaper alternative to permanent structural changes for the introduction of new space-distribution models [7]. Some examples of SEs are tactical urbanism interventions for intersections and street reconfigurations [23,24]; repurposing of street parking spaces with 'parklets' [25]; the repurposing of entire city streets through the approach of 'play streets' [26,27], 'open streets' [28], and 'ciclovías' [29]; and even new district-planning approaches such as car-free superblocks [30,31], district pedestrianisation, and low emission zones [5]; and the 15 min city concept [32,33].

Despite the growing adoption of SEs, particularly accelerated by the demand for expanded public space during the COVID-19 pandemic [34,35], a critical knowledge gap remains. Specifically, there is limited understanding of both local and citywide impacts, as well as of the contextual factors influencing SE effectiveness [36,37]. There is a significant lack of available methods for planners and policymakers to make evidence-based decisions [15] despite the potential of data-driven decision-making to enhance system efficiency, governance, and sustainability [38]. Since urban mobility is becoming increasingly complex, traditional methods may fail to capture the intricate interactions within urban spaces [39] and to address the diverse needs of pedestrians, cyclists, and users of new mobility services such as e-scooters. International indicator frameworks operate at an urban scale, overlooking the scale limitations of local SEs at the street or block level [40–42].

In this context, the paper aims to contribute to closing the gap between the implementation of SEs and the evidence of subsequent impacts by addressing the following research questions (RQs):

(i) RQ1. What limitations do the experimental, temporal, and spatial scope of SEs impose on impact evaluation approaches?
(ii) RQ2. What is the expected impact of adopting SEs from the perspective of EU cities?
(iii) RQ3. How might outdoor data collection technologies support the impact measurement by maintaining the experimental flexibility of SEs?

The structure of the paper is as follows: Section 2 describes the methodological steps followed to address the research questions. Section 3 presents the results from the literature review on evaluation frameworks to assess the impact of SEs and the insights gathered from cities regarding SE goals. This section also includes the proposal for an innovative approach, called the Labkit, to facilitate an in situ and non-intrusive evaluation of SEs. Section 4 provides a critical discussion on the barriers and challenges associated with assessing the success of SEs, together with the opportunities and limitations of the Labkit approach. Finally, Section 5 presents the paper's conclusions and outlines future research directions.

2. Materials and Methods

The methodological steps to address the research questions are based on several activities that allow, firstly, the proposal of an approach to evaluate the success of SEs, considering the limited spatial reach of their impact and the temporal entanglement with wider city trends. Secondly, the identification of expected impacts from cities implementing SEs and the most relevant indicators to measure achievements. Thirdly, data collection technologies are reviewed, and market-ready solutions are explored to collect the variables required. Finally, insights are integrated into an early implementation of the Labkit in an open public space to test its functionalities and inform the design of data pipelines based on real-world data. These steps are further explained below, and a summary is represented in Figure 1.

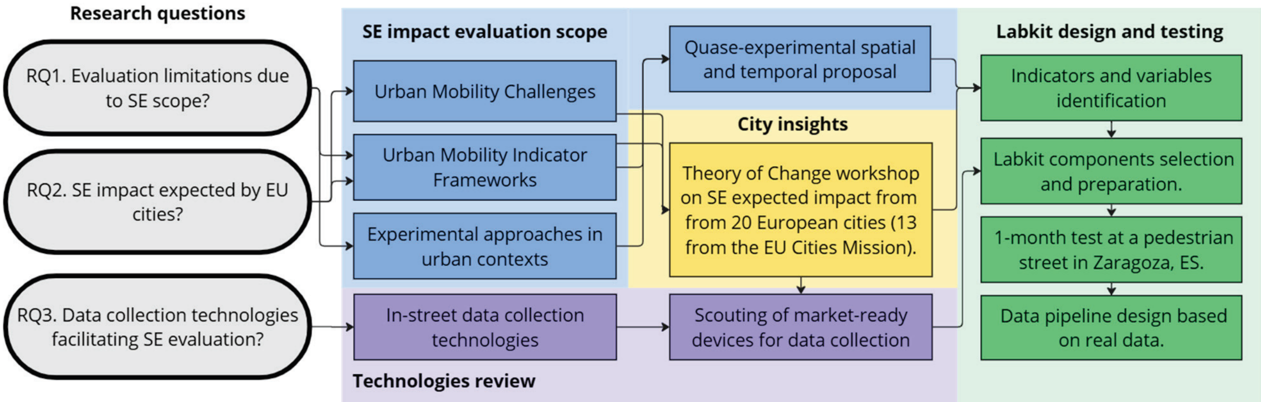


Figure 1. Methodological steps. Source: own elaboration.

2.1. Street Experiments Impact Evaluation Scope

The methodological steps begin with a literature review to establish the scope of an impact evaluation approach tailored to SEs. This review examines urban mobility challenges and opportunities, standardised indicator frameworks, and previous studies on similar evaluation approaches.

In response to the urban mobility challenges outlined in the introduction, SEs emerge as an attractive alternative due to their rapid and flexible approach to testing potential solutions. However, their success depends on multiple factors that must be carefully considered during the impact evaluation to ensure meaningful and context-sensitive results. According to the assessment framework on SEs proposed by Kinigadner et al. [36], the impacts can be categorised into two contexts: system context and experiment context. The system context includes long-term, indirect changes related to policy, financial, and regulatory frameworks, as well as shifts in mindset, norms, and stakeholder networks. For instance, citywide policies may be influenced by SE implementations, leading to the introduction of new regulatory measures (e.g., speed limits), market-based instruments (e.g., taxes), or information-based strategies (e.g., awareness campaigns) [43]. Such policy implications may also be crucial to increasing the adoption and use of active and shared mobility services such as electric-bike-sharing systems [44].

Experiment context impacts include transport-related and sustainability-related changes, which tend to be more immediate, direct, and locally visible than system context impacts. These effects can be monitored before, during, and after the implementation of an SE. Experiment context impacts can be either positive or negative, for instance, changes in public perception towards the acceptance or rejection of a solution, or actual reductions in traffic volumes and safety incidents, or merely their displacement [36].

Despite the reported evidence regarding SEs, there is still a gap in comprehensively understanding the direct effects of measures such as quick street-space reallocation [45,46], tactical urbanism [47], or superblocks [48,49]. Among the types of studies evaluating SE impacts, ex-ante evaluations based on modelling approaches are common [50,51], while other studies assess people's perceptions and choices at the case study level via surveys and observations [5,52]. The air quality and health impacts of SEs tend to rely on environmental monitoring and health surveys for before-and-after comparisons [49].

Another more complex approach applied in transport is the use of quasi-experimental methods to capture the effects of mobility solutions that overlap with other interventions or trends that are likely to generate causal spatial spillover effects [53]. The difference-in-differences (DID) approach, for instance, identifies the effect of a mobility solution by first calculating the change in outcomes over time for both an intervention area and a control area. By differencing these time-based changes, the DID approach removes unobservable factors specific to each area, as well as any shared temporal trend [54]. This approach is also aligned with the quantification of before, business-as-usual (BAU), and after scenarios, as recommended for the evaluation of urban mobility measures [55].

In this regard, the monitoring of changes over time is usually carried out through the definition of key performance indicators (KPIs). Although there is no existing indicator framework to measure such changes at the scale required by local SEs [56], the EU relies on two standards to assess their mobility systems: the Sustainable Urban Mobility Indicators (SUMIs) [57] and the CIVITAS Evaluation Framework [58]. These allow for the identification of urban mobility strengths and weaknesses at the city level, but their main limitation lies in the significant resource requirements and the data management needed to support extensive data collection and complex calculations [59].

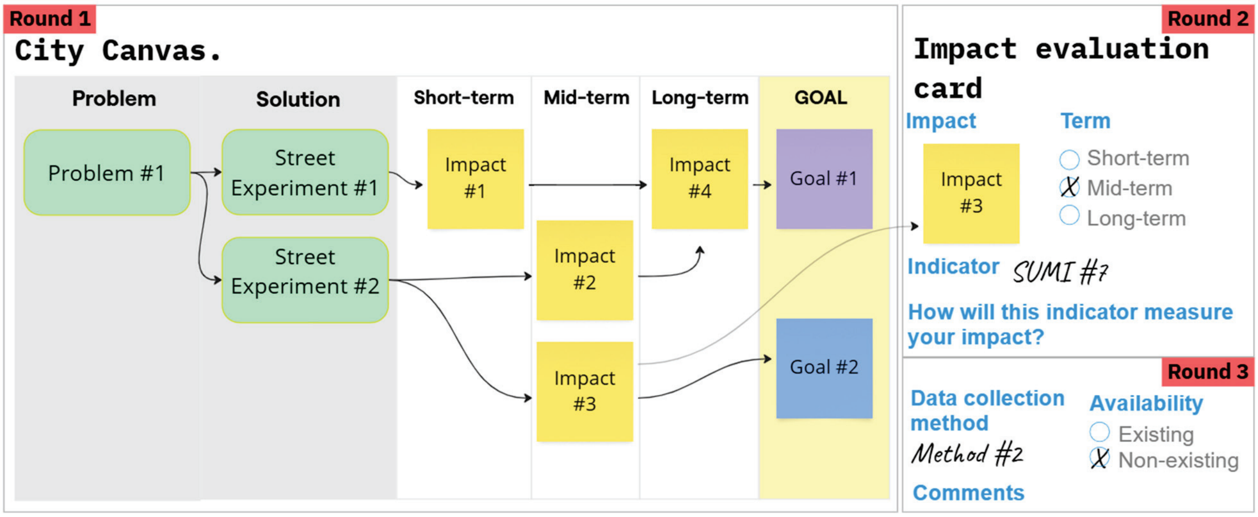
Based on this review, the scope of the impact evaluation framework for SEs is limited to the following: (i) focusing solely on experiment context impacts, which relate to direct, local changes in sustainability and transport; (ii) adopting a DID approach to track changes over time and space; and (iii) leveraging EU indicator frameworks to facilitate debate among the participants cities.

2.2. City Insights: Theory of Change Workshops

To identify the most relevant urban mobility goals and indicators for cities implementing SEs, two workshops were conducted. The first one was organised with 12 cities participating in the European Living Lab on Designing Sustainable Urban Mobility Towards Climate Neutral Cities (ELABORATOR) project: Copenhagen (DK), Helsinki (FI), Milan (IT), Zaragoza (ES), Issy-les-Moulineaux (FR), Trikala (GR), Lund (SE), Liberec (CZ), Velenje (SI), Split (HR), Krusevac (RS), and Ioannina (GR) [60]. Additionally, a second group of eight cities was involved, with the participation of representatives from Amsterdam (NL), Riga (LV), Vilnius (LT), Kozani (GR), Braga (PT), London (UK), Cugir (RO), and Vratsa (BG). In total, 20 European cities, including 13 from the Cities Mission, were involved during this stage.

The workshops were designed using a theory of change (ToC) approach to enable the definition of plausible pathways linking SEs to expected outputs and outcomes, allowing participants to articulate the theories that will drive change [61,62]. The ToC workshop consists of three sequential rounds, with a total duration of one and a half hours. Participants were divided by cities, with each city group composed of city representatives and technicians along with supporting technical partners (e.g., universities, technology centres, etc.). In the first round, cities worked individually, whereas in rounds two and three, cities were paired based on the similarity of their SEs. This collaborative set-up was intended to facilitate the exchange of ideas and best practices, enabling cities to learn from each other's experiences and insights.

During the first round, each city brainstormed expected impacts and goals by first envisioning the problem to be solved and the planned SEs. Participants were encouraged to consider how their projects will address current urban challenges and contribute to the city's future vision. Both impacts and goals were visually mapped on the impact canvas (see Figure 2a) and categorised into short-, medium-, and long-term impacts or end goals of the SE. This visual aid served as a communication tool within the workshop and as a valuable reference for further planning and development.



(**a**) (**b**)

Figure 2. Theory of change workshop materials: (**a**) impact canvas and (**b**) impact evaluation card.

During the second round, cities were asked to complete the first half of the impact evaluation card (see Figure 2b). In this round, participants were required to state each impact from the canvas and select an indicator that could be used to measure it. To facilitate indicator selection, a list describing SUMIs and CIVITAS indicators was provided. This also served to limit the range of options and to ensure comparability across the roundtables. After selecting an indicator, cities explained how it is relevant for quantifying the corresponding impact.

In the final round, based on the selected impact and indicator, cities completed the impact evaluation card by identifying of the most appropriate data collection method. Participants were encouraged to consider the logistical and technical requirements of their data collection strategies in order to move forward with the evaluation of SEs. The cards served as the main output of the workshop, and all the insights from the cities were then processed to identify the most relevant impacts and indicators based on their frequency of selection.

2.3. Technologies Supporting the Impact Evaluation of Street Experiments

During the third methodological step, a review of on-street data collection technologies was performed to initiate the scouting of market-ready devices. The challenges and opportunities of new technological approaches were addressed in two reviews: one on intelligent transport systems (ITSs), covering the literature from 2006 and 2014 [63], and another on smart mobility technology trends from 2011 and 2020 [64]. Although there remains a gap in standardised quantitative frameworks, the main uses of such technologies in urban mobility include (i) continuous data collection for monitoring and management; (ii) smart surveillance for road safety; and (iii) monitoring traffic conditions and real-time responses to emerging situations. Among the technologies enabling such applications, the use of sensors and the internet of things (IoT) are at the forefront of real-time data collection. Other key technologies along the data pipeline include (i) artificial intelligence (AI), (ii) geospatial technologies, and (iii) big data. The latter serves as the foundation layer, processing vast amounts of information from multiple sources to generate actionable insights for mobility planning.

The range of devices for street characterisation varies across several types of sensor technologies and their combinations. The following examples illustrate the diversity of available tools. Personal wearable trackers, composed of GPS receivers and accelerometers, have been tested to monitor walking behaviour and acquire continuous, fine-grained tracks [65,66]. Media access control (MAC) detection via Wi-Fi and Bluetooth probes have been used to analyse visitor trajectories and volumes over time, in transport stations [67], and gated communities [68], and for monitoring pedestrians and cyclists [69]. Infrared counters have been applied to estimate pedestrian presence, movement, and patterns over time and space, for example, in a ten-block urban festival setting [66]. Long-range wide-area networks (LoRaWANs) have been installed in public squares to quantify environmental indicators and the use of public furniture [70]. Smart cameras with image processing capabilities have been employed to monitor social distancing in public spaces and to count vehicles, cyclists, and pedestrians in busy streets [71]. Finally, light detection and ranging (LiDAR) have been applied to 3D modelling of streets [72], as well as to pedestrian and safety monitoring [73].

Despite the wide availability of data collection technologies, an effective impact evaluation framework for SEs requires alignment between methods and the specific context and priorities of cities. This is the aim of the final methodological step, as detailed in Section 2.4.

2.4. Labkit Concept and Design

Finally, this exploratory study contributes to filling the knowledge gap in the impact evaluation of SEs by designing and testing a portable urban mobility laboratory, called the Labkit. As a concept, the Labkit represents an innovative approach that aligns with the characteristics of SEs by enabling in situ, rapid, and non-intrusive measurement of the variables and calculation of indicators required by the cities. Its design integrates the findings from the previous methodological steps, particularly the results of the ToC workshop, into a practical and actionable tool to support cities implementing SEs.

From an operational point of view, the Labkit components must meet the following constraints. First, market-readiness; as the participating cities will be implementing SEs in the short term, there is a need for accurate and reliable technologies. Second, portability, as the Labkit is intended to be an easy-to-install, rapid and flexible solution aligned with the experimental scope of SEs. However, since the Labkit may also support the design of the monitoring layer, the selected technologies should also have the potential to become permanent. Third, non-intrusiveness, due to the sensitivity of data privacy in open urban spaces. Finally, the devices should perform adequately in outdoor conditions, and the technologies should operate effectively at normal urban speeds.

The data collection and analysis pipeline of the Labkit is designed based on a preliminary test in an open urban environment. The chosen area is a pedestrianised street in Zaragoza characterised by constant movement of pedestrians, cyclists, e-scooters, and delivery vehicles. The pilot aims to understand the advantages and limitations of the different types of data collection technologies tested and to inform the design of the Labkit's data pipeline. This exercise does not draw conclusions about the mobility conditions of the monitored area. On the contrary, the site is selected based on the authors' understanding of local mobility trends, allowing the reliability and functionality of the Labkit to be tested.

Once deployed, the Labkit begins the data collection phase. In addition to vehicle, cyclist, and pedestrian counts and speed monitoring, this phase also captures noise levels, air quality parameters, as well as weather conditions without disturbing the urban landscape. The subsequent analysis of the collected data applies analytical methods to transform raw data inputs into actionable insights. This process follows the three steps of a data-driven project applied in transport studies: data collection, data preparation, and data modelling [74]. As presented in Section 3, this process culminates in the calculation of key urban mobility indicators. The limitations encountered during the testing and validation of the Labkit are discussed in Section 4.

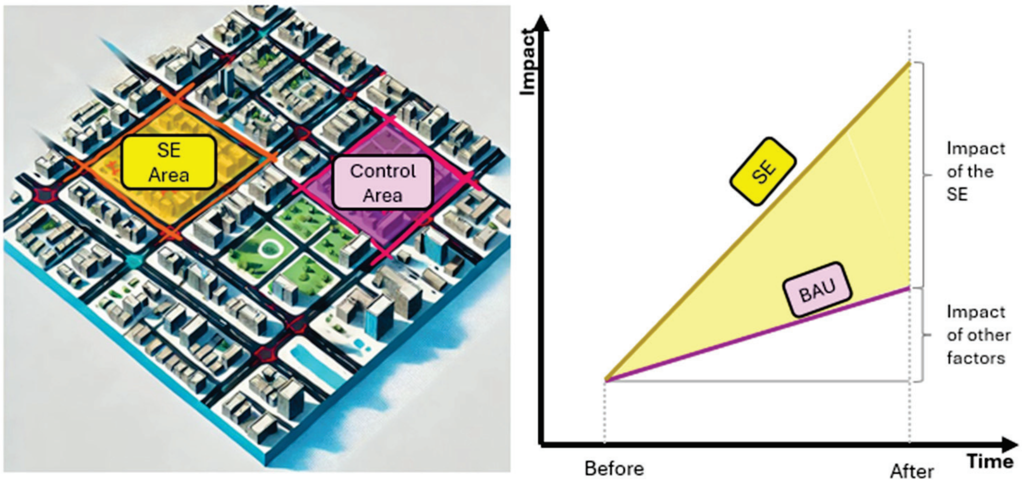
3. Results

3.1. Impact Evaluation Framework for Street Experiments

In the context of transport-related studies, it is not advisable to assume that a behavioural change perceived locally is directly linked to the SE implemented. Transport systems are, by design, networks of interconnected components that interact with the urban environment in various ways. For example, a road safety intervention that results in improvements in one location may lead to the migration of crashes to nearby streets due to the displacement of traffic flows. The effects of a transport intervention may spill over to locations outside the immediate area of influence of an SE, or vice versa [53].

For this reason, the proposed approach to evaluating the impact achieved by an SE follows the quasi-experimental conditions of the DID method. To this end, the following areas are defined: (i) the SE area, where the solution takes place, including the existing transport infrastructure and services, and people travelling through it; (ii) the control area, a comparable space in structure and behaviour that should minimise differences with the SE area to allow comparison; (iii) the surrounding streets of the SE area, where traffic might be diverted, suggesting that any perceived reduction in externalities within the SE area may result from displacement rather than an actual decrease.

As shown in Figure 3, this spatial framework enables a dual evaluation, encompassing the before-and-after comparison within the SE area whilst also incorporating the BAU scenario, as reflected in the trends observed in the control area. This approach considers urban, regional, or global trends (i.e., impact of other factors) that may contribute to the perceived success of the SE. However, these external trends should be subtracted from the difference between the pre-solution (before) and post-solution (after) values to determine the actual impact of the SE (i.e., the changes introduced by the solution).



(**a**) (**b**)

Figure 3. SE impact assessment framework: (**a**) spatial approach and (**b**) temporal approach. Source: adaptation from Riedel et al. [55].

3.2. Indicator Identification and Selection by Cities

The first step in identifying potential indicators in line with the cities' objectives is a review of the literature. SUMIs are categorised based on the type of data sources and different types of mobility solutions they address [57]. Additional indicators are included to complement the existing list of SUMIs, and their categorisation is based on similarity with other indicators and the authors' expertise. Table 1 presents, on the one hand, the most appropriate indicators regarding their frequency of use across six types of interventions: transit-oriented development (TOD), street calming or traffic pacification, car-free planning, creation of cycle lanes, walkable spaces, and implementation of public bike-sharing systems. On the other hand, Table 1 also summarises the indicators selected by cities through the impact evaluation cards completed during the ToC workshop. The final column specifies the frequency with which each indicator was selected and the cities that expressed interest in them.

Among the indicators selected by at least three cities, three groups are defined according to the category of data collection. The first group consists of indicators based on surveys, used to understand users' level of awareness and perception towards the quality, satisfaction, and accessibility of the transport system. These indicators are considered valuable by cities aiming to design a better and safer distribution of public space informed by citizens' opinions. The second group comprises geographic information system (GIS)-based indicators related to the availability and distribution of infrastructure, services, commerce, and facilities that promote active mobility. Cities identify these as fundamental for quantifying the quality of public space. The final group includes indicators derived from urban statistics and databases, covering topics such as safety and accidents, congestion and modal split, as well as environmental indicators such as air pollution and noise. This last group of indicators could be the most appropriate to be quantified using data collection technologies.

Cities identify the improvement in safety and the quality of urban space as their main objective for adopting SEs, with a focus on the most vulnerable users. There is also growing attention to emerging transport modes that increase pedestrian risk, such as e-scooters and other personal mobility vehicles (PMVs). The assessment of road safety impacts usually relies on crash and fatality statistics, which are published every one or two years, a periodicity that does not align with the short-term nature of SEs.

Table 1. Indicators selected by cities and related types of interventions.

SUMIs	Indicator Category	Data Collection Category	Type of Intervention Addressed by Indicators [57]						Frequency of Selection by Cities During the ToC Workshops
			TOD	TP	CFP	BL	WS	BS	
Quality of public space	QL	S	*		*	*	*	*	14: LUN, COP; TRI, HEL, ZGZ; VAL, ISSY, SPL, AMS, MIL, BRA, LND, RIG, VIL
Accidents	QL	DB	×	×	×	×			11: LUN, COP, TRI, HEL, VAL, KRU, LIB, MIL, BRA, LND, VIL
Traffic safety active modes	QL	DB	×	×	×	×			10: LUN, COP, TRI, HEL, VAL, ISSY, SPL, BRA, LND, VIL
Opportunity for active mobility	MSP	GIS	×	×	×	×	×	×	10: LUN, COP, ZGZ, VAL, MIL, AMS, BRA, LND, RIG, VIL
Urban functional diversity	MSP	GIS	*		*		*		8: LUN, COP, ZGZ, HEL, AMS, BRA, LND, RIG
Satisfaction with transport	MSP	S	×						7: LUN, TRI, ZGZ, MIL, KRU, LND, RIG
Air pollutant emissions	QL	DB, S, TM	×	×	×	×	×	×	6: KRU, LUN, ZGZ, BRA, LND, VIL
Noise hindrance	QL	F	×	×	×				6: ION, ZGZ, SPLI, BRA, LND, VIL
Access to mobility services	QL	GIS	×		×				5: TRI, ZGZ, MIL, SPLIT, RIG
Congestion and delays	EC	S, GIS, F	×	×	×	×	×	×	5: LUND, ZGZ, VAL, SPLIT, BRA
Accessibility for mobility-impaired groups	MSP	S	×				×		5: LUN, TRI, MIL, LND, VIL
Security	MSP	S							5: LUN, ION, MIL, RIG, VIL
Mobility space usage	QL	GIS	*	*	*	*	*	*	5: AMS, MIL, BRA, LND, RIG,
Greenhouse gas Emissions	ENV	DB, S, TM	×	×	×	×	×	×	4: ION, ZGZ, BTA, LND
Modal split	MSP	DB, S	×	×	×	×	×	×	3: COP, ZGZ, KRU
Commuting travel time	EC	S	*	*	*	*	*	*	3: TRI, ZGZ, BRA
Multimodal integration	MSP	S, GIS	×					×	3: LUN, MIL, RIG
Affordability for the poorest groups	MSP	DB	×		×				-
Energy efficiency	ENV	DB, S, TM	×		×	×	×	×	-

* Added by the authors. TOD: transit-oriented development; TP: traffic pacification; CFP: car-free planning; BL: bike lane; WS: walkable space; BS: public bike-sharing. QL: quality of life; MSP: mobility system performance; ENV: global environment; EC: economic success. S: survey; DB: based on existing databases; GIS: based on GIS; TM: traffic model; F: field observation. AMS: Amsterdam; BRA: Braga; COP: Copenhagen; HEL: Helsinki; ION: Ioannina; ISSY: Issy-les-Moulineaux; KRU: Krusevac; LIB: Liberec; LND: London; LUN: Lund; MIL: Milan; RIG: Riga; TRI: Trikala; SPL: Split; VAL: Velenje; VIL: Vilnius; ZGZ: Zaragoza.

Cities also expect to have a positive impact on reducing car use and promoting active modes, as well as on reducing the environmental externalities of transport. The main obstacle discussed by the cities is how to effectively measure the impact of conventional city-level indicators, given that SEs are implemented at local scale. A third group of indicators is related to social aspects such as satisfaction, accessibility, and perception towards the transport system. Among topics not covered by the SUMIs, some cities emphasise the importance of considering climate adaptation, nature-based solutions, and spatial justice as trending design criteria.

3.3. Labkit Design and Testing

As previously commented, the Labkit aims to be an in situ, rapid and non-intrusive approach to collect variables and calculate indicators, in line with the flexible nature of SEs. From the exercise with cities summarised in Table 1, the indicators most suitable to be addressed by the Labkit are those that rely on databases and field measurements. Namely, accidents and the safety of active modes, noise, and emissions and congestion and modal split. From this point, the design of the Labkit starts with the matching between the variables to measure the capabilities of data collection technologies.

On the variable side, the indicators for each variable are initially assessed based on definitions from the SUMIs [57,59]. Both accidents and the safety of active modes focus on the number of fatalities caused by road accidents. This approach is slow-paced, as safety statistics are typically published annually or biennially. Noise is calculated as the population exposed to harmful levels, requiring direct field measurements. GHG and air pollutant emissions are calculated using activity factors (i.e., the distance travelled per transport mode and vehicle type) and emission factors (i.e., the quantity of pollutants emitted per unit of energy consumed). This method is suitable for calculating the direct effects of SEs if traffic volume monitoring is measured in the streets within and surrounding the SEs and control areas. Traffic volumes (e.g., cars per hour) are also crucial for assessing modal split and congestion, along with speed and direction. Since SEs typically aim to promote active mobility, pedestrian and cyclist volumes are critical variables. Lastly, based on feedback from the cities, thermal comfort is also considered, as it depends on meteorological data such as air temperature, specific humidity, wind velocity, and mean radiant temperature [75].

On the technology side, several types of devices have been identified to collect the variables mentioned above. These technologies meet the scouting criteria outlined in Section 2: market readiness, portability, non-intrusiveness, and outdoor functionality. In summary, Figure 4 illustrates the alignment between the available device types, variables, and indicators.

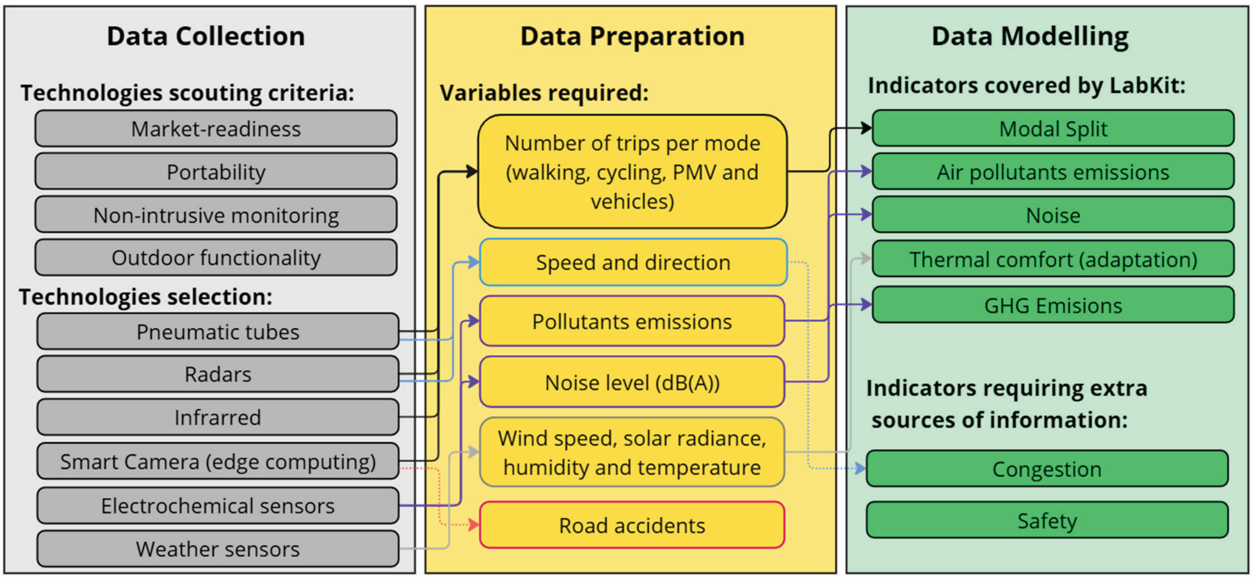


Figure 4. A conceptual framework for the Labkit's design. Source: own elaboration.

As a result, the Labkit is structured around the acquisition of commercially available devices, including pneumatic tubes for traffic and cycling lanes, radars for traffic and pedestrian paths, infrared counters for pedestrians, smart cameras for multimodal counting, and an air quality station equipped with electrochemical sensors for air pollutants and weather conditions. To understand the possibilities and limitations of the technologies aggregated in the Labkit, an early test is conducted on a pedestrian-priority street with low motor traffic and high volumes of bicycles and e-scooters in Zaragoza. As the test does not aim to evaluate the local mobility patterns, no numerical results are presented in order to avoid any misinterpretation of the mobility trends of the test area.

Nevertheless, data are collected to accumulate raw data from each device and to process and transform them into variables and then into the selected indicators. The test is successful for the following indicators: modal split, air pollutants, noise and thermal comfort. For these indicators, all required inputs are correctly measured, and the values are calculated. For congestion, although speeds are recorded for different times of the day, there is no distinction between peak and off-peak periods, as this is a low-speed, low-volume road. This also raises the question of whether congestion as defined by SUMIs is appropriate for a safe and quiet urban environment. In the case of GHG emissions, tailpipe emissions are not measured, this indicator is measured indirectly as CO_2 concentrations. Further testing is needed to determine whether this approach is appropriate. Lastly, safety variables are not collected because the tested smart camera device processes low-resolution images using edge computing. This enables vehicle and pedestrian counting but does not capture the detailed interactions or conflicts needed for safety assessment. These indicators will be considered in a future iteration of the technology scouting. As shown in Figure 5, the results are translated into a visualisation tool as an example of the monitoring potential of the Labkit approach.

(**a**) (**b**)

Figure 5. (**a**) Labkit test and (**b**) visualisation example based on collected data in Zaragoza.

4. Discussion

As debated with cities during the workshops, there is a need for an adequate impact evaluation approach capable of capturing the time- and space-constrained changes generated by SEs. For example, at the ToC workshop, cities questioned how citywide issues, such as GHG emission reductions or congestion decreases, could be effectively addressed given the limited scope of interventions focused on active mobility and improving the safety of pedestrians and vulnerable road users. This mismatch between the scale of impact evaluation and the scale of the SEs can lead to misaligned policies and missed opportunities for targeted improvements. In this sense, the adoption of quasi-experimental approaches might shed light on how effectively SE implementations translate into concrete changes in people's behaviour or into the reduction of transport externalities.

However, cities also highlight concerns about resource constraints—limited budgets, time, or personnel—when attempting to measure mobility simultaneously in both the SE and a control area. Cities require methodological approaches that reduce this burden in terms of the number of externalities to address. SUMIs appear to consider this by including a set of 20 indicators, whereas CIVITAS, although flexible in terms of what cities can choose or discard, proposes more than 50 indicators. Working side by side with cities, as done in the ToC workshops, allows for the identification of the main issues that cities are focusing on. Whether in the form of expected impact, defined goals, or problems to tackle, these activities are useful for prioritising the mobility subjects that a set of indicators should include. Based on the insights gathered, the list of SUMIs could be potentially reduced by half.

In addition, cities are raising awareness towards other issues not covered by these indicator frameworks but which are becoming increasingly relevant when discussing new configurations of urban spaces, particularly in the case of SEs being co-created with citizens. Some participating cities express the need to consider climate adaptation and nature-based solutions, while others aim to go beyond accessibility and assess emerging social concepts such as spatial justice.

Although this study does not fully resolve the issue, the Labkit's design contributes to bridging the gap between macro- and micro-scale evaluation methods, reducing the effort required to address traditional indicators. This approach not only enriches the evaluation and validation of SEs but could also support the definition of concrete lessons learned for policymaking and the promotion of sustainable mobility.

The preliminary evaluation of the Labkit has yielded positive results in terms of identifying the tool's potential to define opportunities and constraints. While key indicators, such as air quality and modal split, can be quantified at the scale of SEs, congestion levels, traditionally based on vehicle speed, present a notable challenge. High speeds can be detrimental to pedestrian safety and discourage walking and cycling. This paradox highlights the need for a revised approach to assessing congestion that considers not only the speed of traffic but also the quality of life and safety of urban spaces. Similarly, reliable and privacy-protecting technologies can help addressing the lack of monitoring of safety and conflicts between modes. Technologies, such as AI cameras and LiDAR, could be tested to assess their potential to analyse traffic patterns and pedestrian behaviour.

Another key benefit observed during these early tests is the Labkit's ability to provide rapid, on-site analysis, a feature that could address some of the resource limitations expressed by cities. Collecting essential mobility information in such a flexible way might be critical for monitoring the SE and control areas, making timely decisions, or encouraging citizen participation. The Labkit's portability and non-intrusive nature ensure that its deployment causes minimal disruption to the existing urban fabric. It can also support the design of the city's data collection infrastructure and the early testing of monitoring and visualisation interfaces.

However, early deployments have also highlighted challenges, mainly regarding the emerging environmental and social issues raised by cities. Further adjustments and complementary activities are needed to adapt the tool more closely with cities' expectations. This approach could extend its applicability to diverse urban environments, ultimately contributing to the development of smarter and more sustainable cities.

5. Conclusions

Regarding RQ1, the main limitation recognised by cities is the difficulty in attributing concrete impacts to local SEs on phenomena that occur at the city or regional level, such as pollution or car dependency. While existing evaluation frameworks provide a foundation, there is a clear need for methodologies tailored to the temporal and adaptive nature of SEs. This is also related to cities' concern towards the resource demand of existing frameworks and the limited budget, time, or personnel that city administrations might allocate to generate solid evidence. On one hand, the need to quantify the real effect of SEs is recognised, requiring the generation of before-and-after and BAU scenarios. On the other hand, this quasi-experimental approach depends on the selection and monitoring of at least two areas, the intervention area and an additional control area, doubling the required effort. All these limitations need to be addressed to assist participating cities in the impact evaluation of SEs and for the generation of evidence-based best practices and policy recommendations.

In the case of RQ2, the ToC workshops resulted in the identification of the expected impacts and goals cities are pursuing through the deployment of SEs, as well as of the mobility fields they aim to address through indicators. The quality of urban space and safety are at the top priorities for implementing SEs that can reallocate car space, reduce speeds, and open streets to people. Encouraging behaviour change towards active mobility and achieving associated local environmental benefits are also key objectives for cities. At a third level, cities highlight concerns related to the quality of the transport system and the perception of citizens. While these goals are directly linked to the experimental context impacts, they are also connected to the system context impacts of SEs, which can generate long-term effects through changes in policies or mindsets [36]. The implementation of SEs might be an opportunity to merge engineering approaches with social sciences approaches to consolidate sustainable mobility.

From this exercise, two key challenges emerge. First, addressing other topics not covered by EU frameworks [58,59] such as climate adaptation and spatial justice—concepts that might be difficult to translate into measurable indicators. Second, evaluating existing indicators to determine whether they are appropriate for assessing the goals of SEs. For instance, current practices for measuring safety and congestion may not fully reflect the impacts targeted by these interventions.

Finally, insights about RQ3 are based on the design and pilot trial of the Labkit. The Labkit has demonstrated significant potential in initial field trials to support how cities approach the measurement and analysis of SEs. Although the Labkit currently addresses only a subset of the identified indicators, its ability to conduct non-intrusive, in situ evaluations enables the agile adaptation of public spaces. Future research should focus on integrating GIS- and survey-based methods to provide a more comprehensive data collection framework. Such integration would enhance the Labkit's outputs by encompassing a broader range of indicators.

Additionally, future research should include continued collaboration with cities to develop a tailored evaluation methodology that integrates the quasi-experimental approach with city expectations and constraints. This would be a valuable development to provide evidence-based insights into the transformations driven by SEs and to help cities identify best practices and replication opportunities. However, this will require addressing several challenges, such as minimising resource demands considering cities' budget and personnel constraints. Further concerns include potential inconsistencies and issues of scalability, which may affect the comparability of results and the harmonization of approaches across EU cities. The reliance on local data also presents challenges, particularly if the data are incomplete or of poor quality. To begin tackling these challenges, a key next step would be to conduct a comprehensive literature review of indicators that are better suited to the nature of SEs, while also incorporating emerging concepts such as mobility justice, nature-based solutions, and climate adaptation.

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Green Concrete Production Technology with the Addition of Recycled Ceramic Aggregate

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Abstract: Rational waste management is crucial for the effective implementation of the circular economy (CE) and the achievement of Sustainable Development Goals (SDGs). Ceramic waste, which takes thousands of years to decompose in the natural environment, can be recycled into construction materials. This approach offers dual environmental benefits: reducing ceramic waste disposal and minimizing the exploitation of natural aggregate deposits. This study examines the recycling of sanitary ceramic waste, including items such as washbasins, toilet bowls, urinals, bidets, and bathtubs, into alternative aggregates for concrete mixtures. After grinding and separating the ceramic cullet into specific fractions, it becomes a viable substitute for natural aggregates. Concrete samples were tested with varying water-cement ratios (0.3 and 0.4) and recycled ceramic aggregate contents (15%, 30%, and 45%). These results were compared to those of samples made solely with natural aggregates. The samples underwent compressive strength tests to determine concrete class and were exposed to elevated temperatures (150 °C, 300 °C, 550 °C, and 750 °C). Additional analyses measured the secant modulus of elasticity and selected aggregate properties. The findings demonstrate that high-quality concrete can be produced while promoting circular economy principles by reducing waste and preserving natural resources.

Keywords: ceramic cullet; recycled concrete; circular economy; green concrete

1. Introduction

One of the priority goals of the contemporary world is to promote a circular economy, which is an idea minimizing environmental burdens by introducing rational economic solutions [1,2]. The construction industry has long been one of the most environmentally impactful sectors of the economy [3]. In order to reduce the destructive impact of civil engineering on ecosystems, efforts are being made to reduce material consumption, especially natural resources, and minimize waste generation [4,5]. Waste generated by the construction sector includes, among others: concrete, asphalt, ceramics, steel, tires, polyethylene terephthalate (PET), slag, and ashes. Storing these wastes in landfills leads to contamination of adjacent soils, air, and water, and the limitation of available space for local communities [6].

The introduction of the circular economy concept in the construction industry primarily occurs through the use of recycling in the production of building materials. It is becoming increasingly common to utilize recycled aggregates in concrete, particularly in concrete pavements but also in other civil engineering structures [7]. According to estimates [8,9], the concrete industry annually requires 1.5 billion tons of cement, 10–20 billion tons of aggregates, and approximately 1 billion tons of water for concrete production. This means that introducing alternative solutions in concrete technology opens the door to efficient recycling of construction and industrial waste [10].

Green concretes are most often produced by incorporating recycled aggregate or modified cements into the mix. The use of eco-friendly cements containing waste substances allows for the production of materials with similar or sometimes even better mechanical properties compared to traditional cements [11,12].

Aggregates occupy a large portion of the volume in concrete, approximately 80%, and are a fundamental factor in shaping the compressive strength of the hardened material [13]. The most commonly used recycled aggregates in concrete are from demolished concrete and ceramics [14].

Recycled ceramic aggregate consists of finely crushed roof tiles and bricks made of red ceramics, along with ceramic tiles and sanitary ceramics, which are the focus of research studies [15,16]. Waste from sanitary ceramics includes chipped and cracked sanitary ware, rejected during quality control, such as: toilet bowls, sinks, bidets, bathtubs, and urinals [17]. The manufacturing of sanitary products includes shaping, drying, and glazing semi-finished items, followed by firing at approximately 1200 °C [18].

The utilization of finely crushed recycled sanitary ceramic aggregate (ceramic cullet) in concrete technology requires experimental analysis of the properties of mixtures containing ceramics. Concrete must absolutely meet durability requirements during its service life [19]. The lack of standards and guidelines for designing mixtures based on ceramic aggregate means that concrete production relies on experimental analysis of the relationship between secondary aggregates, cement, natural aggregates, and other mixture components [20].

According to a few studies addressing the incorporation of sanitary ceramics into concrete mixtures, partial replacement of coarse aggregate with ceramic aggregate positively affects the strength characteristics of the hardened material [17,21,22]. Research [21] has shown an improvement in compressive strength after the application of recycled ceramics in the mixture, a reduction in the porosity of the concrete structure, and an increase in the bond between the cement matrix and the aggregate [23]. Furthermore, this concrete exhibited higher resistance to freeze-thaw cycles [24] and elevated temperatures [25]. This results from the ceramic aggregate's low thermal expansion coefficient [18,24,26].

Important factors in waste management are financial considerations and the costs associated with implementing a particular solution on a larger scale. Introducing sanitary ceramic aggregate into concrete enables the production of inexpensive and durable material, which contributes to solving environmental problems [17]. This direction should be promoted due to the high durability of sanitary ceramics, which undergo biodegradation over more than 4000 years [27].

This article describes the author's research results on compressive strength, compressive strength after roasting, and shear modulus of elasticity under compression. The preparation and curing of samples were conducted using commonly used procedures, following construction standards. The concrete production conditions aimed to demonstrate the possibility of achieving a high-quality material containing recycled ceramic aggregate without additional financial outlay associated with the use of complex and hard-to-access technologies, equipment, and materials.

2. Materials and Methods

To determine the composition of the concrete mix, the density and absorption of the coarse aggregates were analyzed. Samples for testing comprised weighed portions of granite and recycled ceramic aggregate. The determinations were conducted in accordance with the recommendations of European standard [28], using the pycnometer method for aggregates with particle sizes ranging from 4 mm to 31.5 mm.

Specimens for strength testing were prepared in accordance with European standard [29]. For compressive strength and compressive strength after roasting tests, cubic samples with dimensions of 100 × 100 × 100 mm were used. For the determination of modulus of elasticity, cylindrical samples with a diameter of 150 mm and a height of 300 mm were employed. After molding, the samples were stored in air-dry conditions for 48 h. Subsequently, they were removed from the molds and submerged in a water tank to reach full saturation. The tests were conducted 28 days after the samples were made, ensuring the standard concrete curing period.

The determination of compressive strength was carried out based on the guidelines outlined in European standard [30]. After removing the samples from the tank to ensure full saturation of the concrete, they were dried to remove excess moisture. Subsequently, three measurements were taken for each side of the sample using a caliper to determine the cross-sectional area subjected to compressive force. The samples were positioned in the testing machine (ToniTechnik PACT II, ToniTechnik GmbH, Schrobenhausen, Germany) so that the load was applied perpendicular to the direction of the cube formation during concrete casting. To obtain values for analysis, the test results were converted using an appropriate scaling factor of 0.90 for cubic samples with a side length of 100 mm compared to samples with a side length of 150 mm [31].

After 28 days from the preparation of the samples intended for compressive strength testing after roasting at elevated temperatures, the samples were transferred from the tank to a rack for drying. After 7 days, the concrete was roasted in a muffle furnace type FCF 12SP (LAC, Židlochovice, Czech Republic). The investigation of the impact of elevated temperatures on the strength of the concrete was conducted in four temperature variants—150, 300, 550, and 750 °C. The furnace temperature was increased following guidelines from the Fire Academy (Warsaw, Poland): 150 °C was reached in 30 min and maintained for an hour. Subsequently, reaching 300 °C took another 30 min, and it was maintained for another hour. Reaching 550 °C took an additional 40 min, and it was maintained for an hour, while reaching 750 °C took 50 min, and it was maintained for 30 min. After heating, the samples were left in the furnace until completely cooled. The roasted cubes were subjected to compressive strength testing.

The determination of modulus of elasticity was conducted according to European standard [32] in press C088-11N (Matest, Arcore, Italy). Method A enables the determination of both the initial and stabilized modulus of elasticity. The loading and unloading cycles followed the pattern shown in Figure 1. The compressive strength, tested on cylindrical samples and required for calculating stresses σa and σb, was obtained by converting the strength from cubic samples (15 × 15 × 15 cm) using a scaling factor of 0.80 [22,31].

The binder used for sample preparation was CEM I 42.5R cement (from Górażdże Cement S.A., Chorula, Poland), known for its high early strength and significant heat of hydration. This type of cement is commonly used for ordinary concrete classes but can also be suitable for high-strength concrete applications.

This study utilized two types of coarse aggregates: granite base aggregate and recycled ceramic aggregate (ceramic cullet), derived from finely crushed sanitary ware. The recycled aggregate was obtained from the Sanitec Koło factory (Włocławek, Poland). Before determining the composition of the concrete mixtures, properties of aggregates such as grain density and water absorption were examined. Both properties were necessary to consider in determining the proportions between the mixture components. The water absorption values were WA24 0.73% for granite and WA24 3.92% for recycled ceramic aggregate. The grain density of ceramic cullet was 2.38 g/cm^3 in its dried state and 2.59 g/cm^3 after saturation followed by initial surface drying. In comparison, the density of dried granite grains reached 2.56 g/cm^3, increasing to 2.61 g/cm^3 after saturation and initial drying. Aggregate absorption directly affects the consistency of the concrete mixture. Since absorbed water is excluded from the water/cement ratio calculations, pre-wetting of the aggregates was necessary to achieve the desired w/c ratio. For this purpose, the amount of water absorbed by granite and ceramic cullet was experimentally determined. After wetting the aggregates to full saturation, they were spread out and air-dried under laboratory conditions for one hour to remove surface water. This method was experimentally determined by monitoring the water content in the aggregates at various drying intervals, with the optimal drying time found to be 60 min [22].

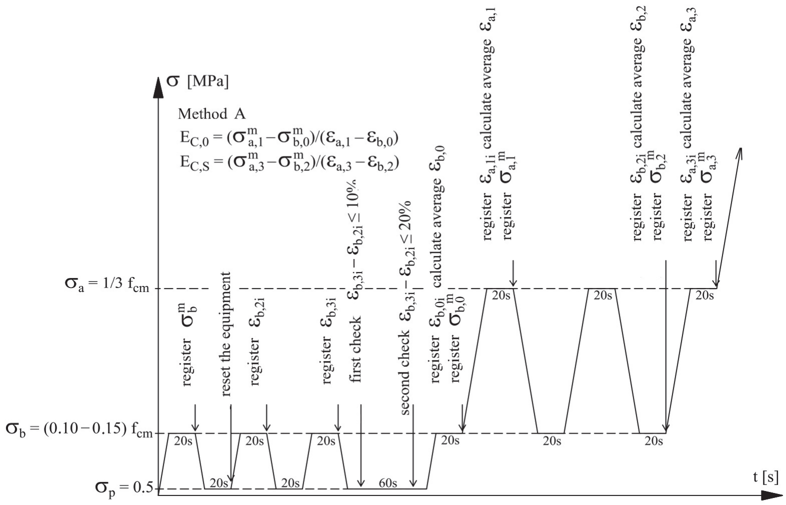


Figure 1. Method A—Load diagram for measuring the initial and stabilized secant modulus of elasticity [22,33].

It was assumed that aggregates with particle size fractions of 4–8 mm and 8–16 mm (Figure 2) would be used. Each fraction ultimately comprised 50% of the total coarse aggregate content in the concrete mix. Eight batches were prepared in total, differing in water/cement ratio and the level of ceramic aggregate recycling in the mixture. The reference concrete, used as the benchmark for all tests, contained only natural granite aggregate. Sanitary ceramics were introduced as a substitute for coarse aggregate, replacing 15%, 30%, and 45% of the granite base aggregate.

To evaluate the impact of ceramic cullet on concrete properties, tests were conducted on mixtures with two water/cement ratio variants: $w/c = 0.30$ and $w/c = 0.40$. The following designations were used: A0, A15, A30, and A45 for $w/c = 0.40$, and B0, B15, B30, and B45 for $w/c = 0.30$. Here, 0, 15, 30, and 45 represent the percentage substitutions of granite aggregate with recycled ceramic aggregate. The selection of replacement levels was made experimentally, assuming a gradual and uniform increase while ensuring a clear distinction between the tested variants. Each series was designed to achieve the S3 consistency class, determined using the slump cone method because it ensures a plastic consistency, which facilitates easy handling and placement of the mix without workability issues. A water-reducing admixture was incorporated to achieve this target. A polycarboxylate-based superplasticizer was employed to significantly reduce mixing water requirements while ensuring proper workability and minimizing segregation and drying shrinkage. The compositions of the prepared concrete mixtures are detailed in Tables 1 and 2. The research cycle included testing the compressive strength of hardened concrete, the modulus of elasticity, and the compressive strength after subjecting the samples to thermal loads.

(**a**) (**b**)

Figure 2. Recycled ceramic aggregate used in the research: (**a**) aggregate grain size 4–8 mm, (**b**) aggregate grain size 8–16 mm.

Table 1. Composition of the concrete mixes when w/c = 0.40 [22].

Component	**Amount in the Concrete Mix [kg/m^3]**
Ingredients in each series (with a constant content)	
Sand	469
Water	180
Superplasticizer	1.350
Cement	450
100% base aggregate—A0 mix	
Granite, fraction 4–8 mm	633
Granite, fraction 8–16 mm	633
15% ceramic cullet—A15 mix	
Granite, fraction 4–8 mm	538
Granite, fraction 8–16 mm	538
Cullet, fraction 4–8 mm	95
Cullet, fraction 8–16 mm	95
30% ceramic cullet—A30 mix	
Granite, fraction 4–8 mm	443
Granite, fraction 8–16 mm	443
Cullet, fraction 4–8 mm	190
Cullet, fraction 8–16 mm	190
45% ceramic cullet—A45 mix	
Granite, fraction 4–8 mm	348
Granite, fraction 8–16 mm	348
Cullet, fraction 4–8 mm	285
Cullet, fraction 8–16 mm	285

Table 2. Composition of the concrete mixes when w/c = 0.30 [22].

Component	Amount in the Concrete Mix [kg/m^3]
Ingredients in each series (with a constant content)	
Sand	501
Water	135
Superplasticizer	6.30
Cement	450
100% base aggregate—B0 mix	
Granite, fraction 4–8 mm	677
Granite, fraction 8–16 mm	677
15% ceramic cullet—B15 mix	
Granite, fraction 4–8 mm	575
Granite, fraction 8–16 mm	575
Cullet, fraction 4–8 mm	102
Cullet, fraction 8–16 mm	102
30% ceramic cullet—B30 mix	
Granite, fraction 4–8 mm	474
Granite, fraction 8–16 mm	474
Cullet, fraction 4–8 mm	203
Cullet, fraction 8–16 mm	203
45% ceramic cullet—B45 mix	
Granite, fraction 4–8 mm	372
Granite, fraction 8–16 mm	372
Cullet, fraction 4–8 mm	305
Cullet, fraction 8–16 mm	305

3. Results

The compressive strength and compressive strength after heating were determined using six samples from each analyzed series. Additionally, the secant modulus of elasticity under compression was calculated based on the results from three cylindrical samples. The results of these tests are summarized in Table 3.

Measurement uncertainty was determined exclusively for the compressive strength test results. The determination of the secant modulus of elasticity was conducted with the minimum number of samples, and therefore, statistical analysis was not included. Measurement uncertainties were determined using the t-Student distribution, with a 95% confidence interval [22].

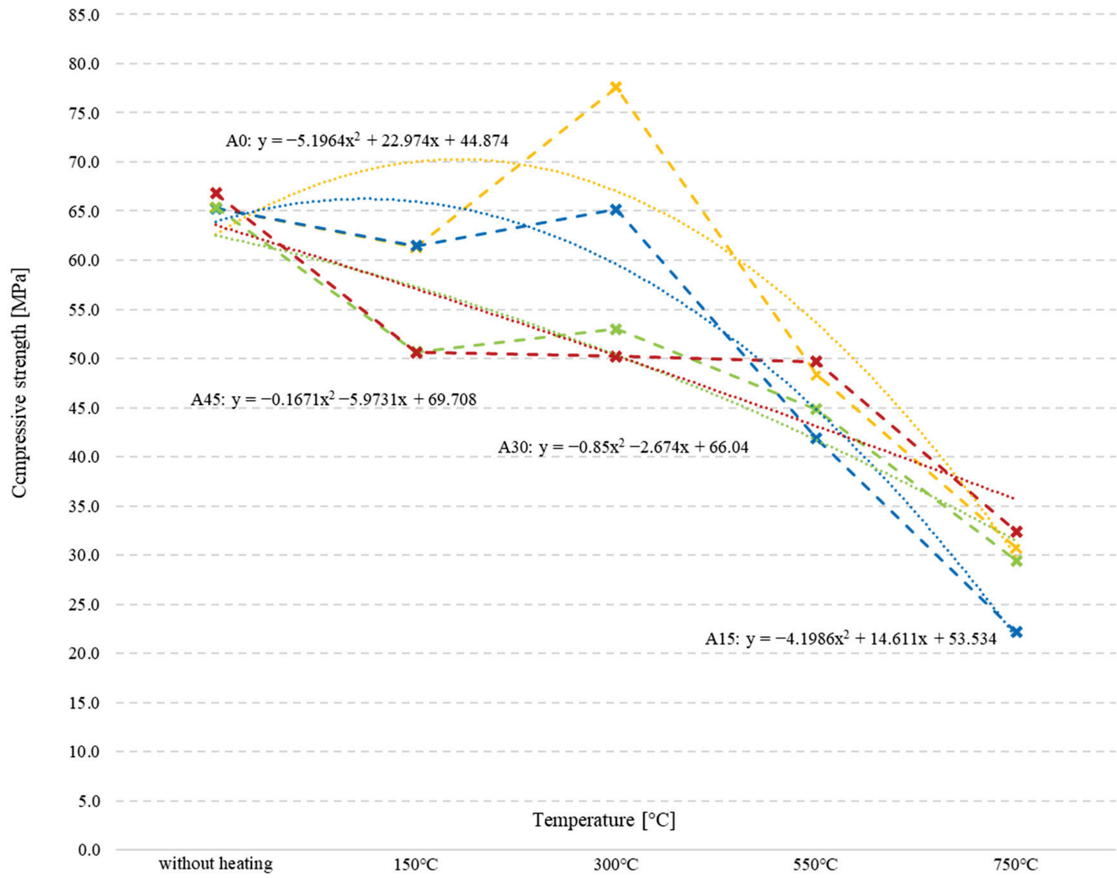
Table 3. Results from testing the concrete.

Feature of Concrete	100% of Granite Aggregate		15% of Ceramic Cullet		30% of Ceramic Cullet		45% of Ceramic Cullet	
	A0	B0	A15	B15	A30	B30	A45	B45
w/c ratio	0.40	0.30	0.40	0.30	0.40	0.30	0.40	0.30
Compressive strength f_{cm} [MPa]	65.3	95.9	65.3	78.2	65.4	78.7	66.8	76.9
Measurement uncertainty of compressive strength results [MPa]	±0.81	±2.43	±0.61	±1.27	±0.45	±1.04	±0.56	±0.81
Compressive strength after heating at 150 °C [MPa]	61.3	79.2	61.5	78.8	50.7	49.9	50.6	49.9
Measurement uncertainty of compressive strength after heating at 150 °C [MPa]	±1.71	±1.02	±2.61	±0.60	±1.48	±0.53	±0.74	±0.32
Compressive strength after heating at 300 °C [MPa]	77.5	81.5	65.2	82.1	53.0	50.0	50.3	49.9
Measurement uncertainty of compressive strength after heating at 300 °C [MPa]	±1.22	±0.41	±3.45	±0.81	±0.33	±0.33	±0.50	±0.28
Compressive strength after heating at 550 °C [MPa]	48.3	70.8	41.9	64.6	44.8	50.0	49.7	49.3
Measurement uncertainty of compressive strength after heating at 550 °C [MPa]	±1.65	±10.29	±4.80	±5.63	±4.75	±0.34	±1.30	±2.05
Compressive strength after heating at 750 °C [MPa]	30.7	53.4	22.2	40.2	29.4	40.9	32.4	42.8
Measurement uncertainty of compressive strength after heating at 750 °C [MPa]	±5.07	±6.51	±5.44	±6.75	±4.82	±8.16	±5.16	±3.76
Initial secant modulus of elasticity $E_{C,0}$ [GPa]	26.5	32.3	28.0	30.8	29.2	34.2	29.5	35.5
Stabilized secant modulus of elasticity $E_{C,s}$ [GPa]	35.4	42.9	35.3	37.2	35.3	37.3	34.6	37.3
Concrete strength class	C50/60	C70/85	C50/60	C55/67	C50/60	C55/67	C50/60	C55/67

4. Discussion

The compressive strength tests revealed that for concretes with a water/cement ratio of 0.40, the strength changes slightly with varying percentages of ceramic aggregate. For concretes with a w/c ratio of 0.30, the addition of ceramic aggregate resulted in a decrease in strength (over 20%). However, no significant differences (up to 2%) were observed between samples containing 15%, 30%, or 45% recycled aggregate.

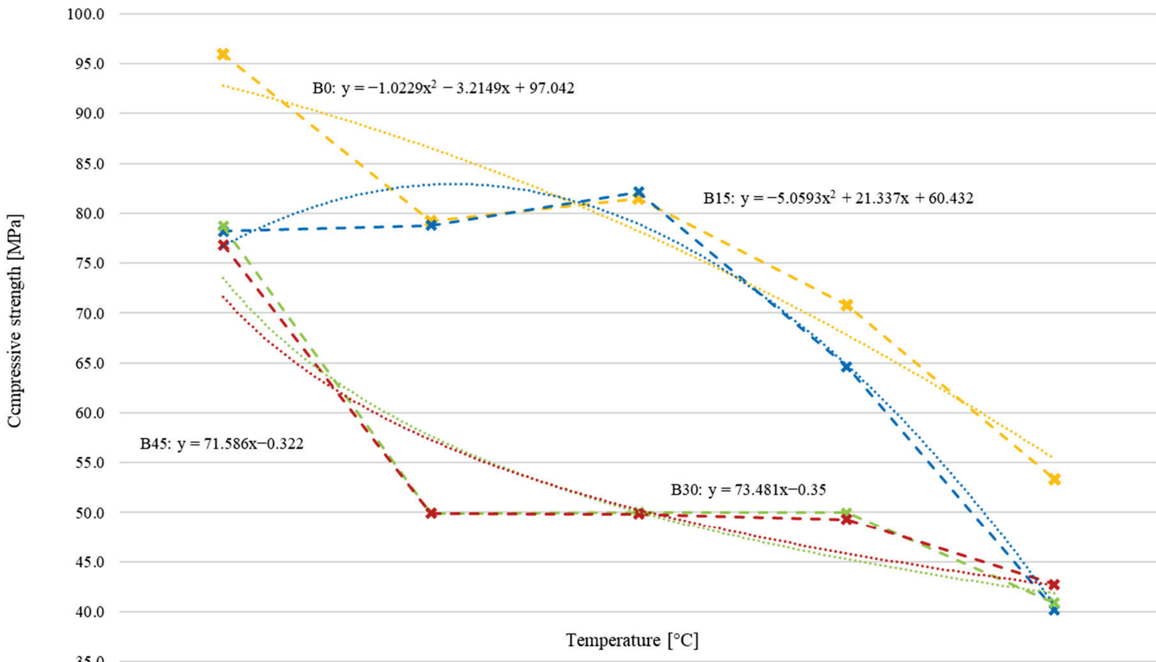
For concretes with a water/cement ratio of 0.40 subjected to heating at 150 °C, 300 °C, 550 °C, and 750 °C (Figure 3), the presence of ceramic cullet improved the material's resistance to elevated temperatures (550 °C and 750 °C). The compressive strength of unheated samples varied slightly (up to ~2.5%) regardless of the concrete composition. After heating at 150 °C, there was a decrease (about 20%) in strength between concrete without cullet and concrete containing ceramics at 15% of the mass of coarse aggregate, and between concrete with ceramic cullet at 30% and 45%, respectively. At 300 °C, there was an increase in compressive strength for A0 (~25%), A15 (~5%), and A30 (~5%) compared to their respective strengths at 150 °C, while A45 showed a slight decrease. At 550 °C, the strength increased as the proportion of ceramic cullet in the concrete rose. The highest strength was achieved by the recycled concrete containing 45% ceramic aggregate (A45). This strength was approximately 3% higher than the base concrete (A0, 100% granite), 17% higher than A15, and 10% higher than A30. After heating at 750 °C, the highest strength was achieved by concrete A45, which was about 5% higher than A0, 45% higher than A15, and 10% higher than A30.



	without heating	150°C	300°C	550°C	750°C
A0 (100% granite)	65.3	61.3	77.5	48.3	30.7
A15 (15% ceramic cullet)	65.3	61.5	65.2	41.9	22.2
A30 (30% ceramic cullet)	65.4	50.7	53.0	44.8	29.4
A45 (45% ceramic cullet)	66.8	50.6	50.3	49.7	32.4

Figure 3. The compressive strength chart of concrete with a water/cement ratio of 0.40 as a function of heating temperature.

The compressive strength test on concrete samples with a water/cement ratio of 0.30 revealed that the inclusion of ceramic cullet aggregate in the concrete mix does not enhance this property (Figure 4). Among the unheated samples, the highest compressive strength was achieved by the reference concrete (B0), which was over 20% higher than the strength of concretes with cullet. Regardless of the percentage of granite replacement, the concretes containing cullet displayed similar strength values. After heating at 150 °C, a significant strength reduction (over 55%) was observed in samples with ceramic cullet (B30 and B45) compared to B0 and B15. At 300 °C, a slight increase in compressive strength was noted relative to 150 °C. The strength of B0 rose by approximately 3%, B15 by 4%, while the strengths of B30 and B45 remained unchanged. At 550 °C, B0 continued to exhibit the highest compressive strength, surpassing B15 by about 10%, B30 by 40%, and B45 by 45%. Following heating at 750 °C, B0 retained the highest strength, though a trend emerged where the strength increased with the proportion of cullet in the concrete. Specifically, B0 demonstrated a strength 30% higher than B15, 31% higher than B30, and 25% higher than B45.



	without heating	150°C	300°C	550°C	750°C
B0 (100% granite)	95.9	79.2	81.5	70.8	53.4
B15 (15% ceramic cullet)	78.2	78.8	82.1	64.6	40.2
B30 (30% ceramic cullet)	78.7	49.9	50.0	50.0	40.9
B45 (45% ceramic cullet)	76.9	49.9	49.9	49.3	42.8

Figure 4. The compressive strength chart of concrete with a water/cement ratio of 0.30 as a function of heating temperature.

The secant modulus of elasticity was evaluated in two variants (Figure 5)—initial ($E_{C,0}$) and stabilized ($E_{C,S}$). For concrete with a water/cement ratio of 0.4, the initial modulus of elasticity gradually increased with the replacement level of granite aggregate by recycled ceramic aggregate. In concrete samples with a water/cement ratio of 0.3, the initial addition of ceramic cullet led to a reduction in the secant modulus compared to samples without ceramic aggregate. As the proportion of cullet in the mix increased, the secant modulus gradually improved.

For samples with a w/c ratio of 0.4, the stabilized secant modulus remained consistent regardless of the amount of granite aggregate replaced by ceramic cullet. In contrast, for samples with a w/c ratio of 0.3, a slight decrease in the stabilized modulus was observed after introducing ceramic cullet. Samples without cullet showed results approximately 15% higher than those with partial aggregate replacement. However, concrete mixes containing 15%, 30%, and 45% recycled ceramic aggregate exhibited almost identical stabilized modulus values.

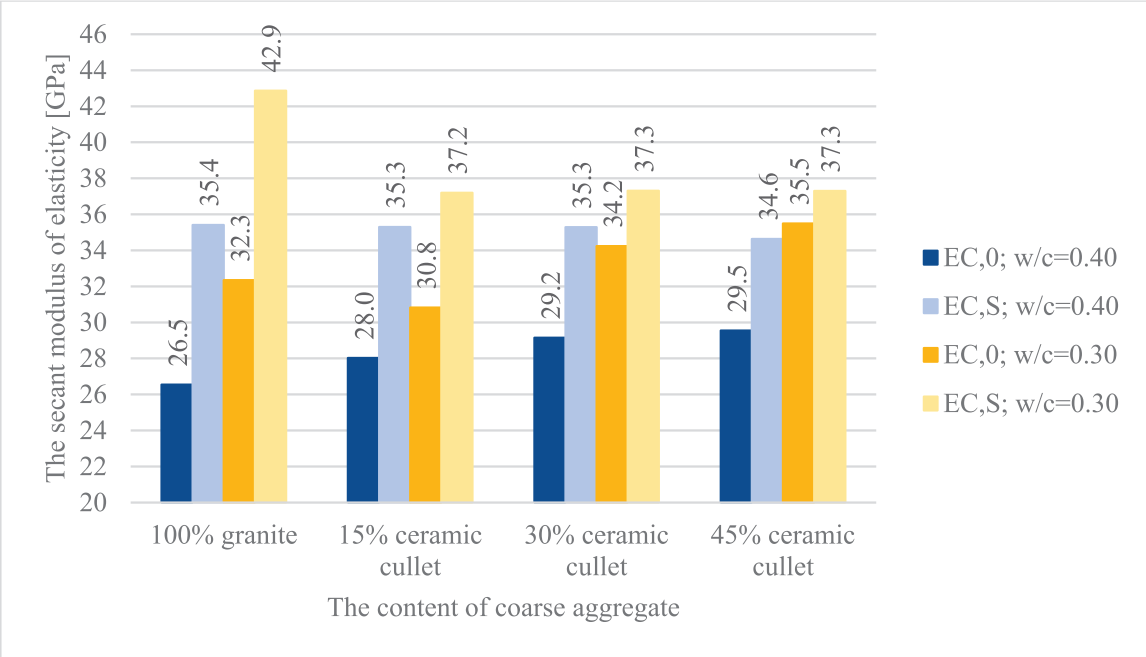


Figure 5. The test results for the secant modulus of elasticity. Reprinted with permission from Ref. [22]. 2024, Mater. Bud [20].

5. Conclusions

The compressive strength test results indicate that for concrete with a water/cement ratio of 0.30, the introduction of recycled ceramic aggregate into the mix led to a significant reduction in strength (by over 20%). In series where 15%, 30%, and 45% of the granite coarse aggregate was replaced with ceramic aggregate, the compressive strength values were similar, averaging around 78 MPa. For all series with a w/c ratio of 0.40, the results remained consistent, averaging approximately 66 MPa. This suggests that the addition of ceramic aggregate had no notable impact on the compressive strength of the concrete at this w/c ratio.

The compressive strength test results after heating reveal that higher ceramic aggregate content enhances the thermal resistance of concrete, particularly at temperatures of 550 °C and 750 °C. This effect was more pronounced in concrete with a water/cement ratio of 0.40, where replacing 45% of granite with ceramic aggregate yielded the highest compressive strengths at elevated temperatures.

In contrast, concrete with a water/cement ratio of 0.30 achieved its highest compressive strengths in the series made exclusively with granite aggregate. However, it is plausible that at replacement levels exceeding 50%, the compressive strength could surpass that of lower replacement ratios. Additionally, for all tested series, an increase in strength was observed after heating to 300 °C compared to 150 °C. This behavior suggests that the evaporation of free water contributed to strengthening the concrete, followed by a gradual decline in strength as dehydration progressed. The observed strength increase may also be linked to the presence of a superplasticizer, which optimizes water distribution within the concrete matrix. To comprehensively understand these phenomena, further research focusing on the rheological characteristics of concrete is recommended.

By incorporating crushed ceramic aggregate in appropriate proportions, it is possible to produce concrete with enhanced resistance to elevated temperatures compared to conventional granite aggregate-based concrete. The results of the conducted research confirm the validity of the proposed theses, indicating that the addition of ceramic waste significantly enhances the thermal resistance of concrete. The obtained findings are consistent with previous reports [33,34], while also expanding the understanding of the mechanisms by which ceramics influence the properties of concrete under high-temperature conditions.

The replacement of natural granite aggregate with ceramic aggregate also resulted in an increase in the initial secant modulus of elasticity. When 45% of the granite aggregate was substituted, this increase reached approximately 10%. This trend was consistent for mixtures with both water/cement ratios of 0.30 and 0.40. The initial secant modulus of elasticity under compression is particularly relevant in prestressed concrete structures, as it affects calculations of instantaneous prestress loss and initial deflection [35]. The observed increase in the initial modulus of elasticity highlights the potential for using recycled ceramic aggregate in prestressed concrete applications. The prospect of using the material in such complex implementations requires a broad analysis of the durability, shrinkage, and corrosion resistance of concrete.

The stabilized secant modulus of elasticity for concrete with a w/c ratio of 0.40 showed minimal variation, regardless of the proportion of recycled ceramic aggregate. For mixtures with a w/c ratio of 0.30, the introduction of sanitary ceramics led to a slight decrease in modulus values. However, across all tested proportions of crushed ceramic aggregate (15%, 30%, 45%), the results were relatively consistent.

The modulus of elasticity of concrete reflects the elasticity of its aggregate and the bond between the aggregate and the cementitious matrix. The results demonstrate that recycled ceramic aggregate can maintain the stress–strain relationship in concrete at levels comparable to granite aggregate [20].

These findings confirm that sanitary ceramics can serve as a viable substitute for coarse aggregate in concretes subjected to thermal loads. Designing concrete mixtures with recycled ceramic aggregate requires careful experimental evaluation of both fresh and hardened concrete properties, particularly concerning durability under anticipated service conditions.

Additionally, we agree that a detailed analysis of the interfacial transition zone (ITZ) between ceramic aggregates and the cement matrix would provide important insights into the microscopic mechanisms affecting strength variations. To address this, future research will focus on conducting SEM and XRD analyses to investigate the microstructure of the concrete more thoroughly, helping to deepen our understanding of the material's performance under various conditions.

In summary, replacing granite aggregate with ceramic aggregate helps reduce the extraction of natural resources. Utilizing recycled ceramic waste can also decrease expenses related to disposal and the transportation of natural aggregates. Additionally, producing recycled ceramic aggregates may require less energy than extracting and transporting natural aggregates. The improved thermal resistance of concrete containing ceramics can result in benefits, particularly in demanding environments such as tunnels or power plants. Furthermore, the advancement of recycled concrete technology can drive innovation in the construction industry and create new job opportunities in the waste processing sector.

The use of recycled ceramic aggregates offers numerous economic, social, and environmental benefits. However, their widespread adoption requires further research and technological optimization. Large-scale implementation necessitates a comprehensive microstructural analysis, long-term durability assessments (including shrinkage and corrosion resistance), and an evaluation of practical cost implications. While ceramic recycling can lower raw material costs, the need to adapt production technology and construction standards may increase overall implementation expenses.

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Abbreviations

The following abbreviations are used in this manuscript:

f_{cm}	compressive strength [MPa]
$E_{C,0}$	initial secant modulus of elasticity [GPa]
$E_{C,S}$	stabilized secant modulus of elasticity [GPa]

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sustainability

Article

Mapping Opportunities for Floating Urban Development Along Italian Waterfronts

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Abstract: In Italy, the number of people living in coastal areas reaches 70% of the total population. By the end of the century, the sea level rise estimated along Italian coasts is between 1.31 and 1.45 m on a non-conservative basis. Considering its high vulnerability to rising sea levels and flooding, Italy holds a strong potential for floating urban development due to its extensive coastline and inland hydrographic network. The main drivers of floating urban development include these increasing threats posed to waterfront communities and the shortage of land for urban expansion, food production, and energy harvesting. However, not all waterfront areas are suitable for accommodating urban development on water because of site-specific urban, social, cultural, infrastructural, climate, and hydrographic features. This paper presents the results of a geospatial analysis carried out using geographic information systems and a statistical analysis of instrumental measurements to map the most suitable regions for floating urban expansion along Italian waterfronts. The mapping identifies six potential zones of interest marked by the co-existence of environmental and socio-urban needs. This study reveals how coastal–riverine interface zones are generally more susceptible to the cumulative effects of climate change and, at the same time, are centers of intense economic, cultural, and social activity.

Keywords: floating urban development; sea level rise; flooding; waterfront; adaptation; urban mapping; GIS mapping

1. Introduction

In Europe, about 86 million people (19% of the entire population) are estimated to live within 10 km of the coastline [1]. In contrast, most of the Mediterranean population (about 75%) lives in coastal areas. The most critical areas in the Mediterranean include the coasts of Turkey [2], the Northern Adriatic [2,3], the Aeolian islands [4], the coast of central Italy [5], and Eastern Morocco [6]. In Italy, where coasts stretch for more than 7500 km, the number of people living in coastal areas reaches 70% of the total population.

The EC Flood Risk Area viewer launched in October 2023 shows the potential flood risk areas identified by each member state under the Floods Directive. According to this map, Italy is highly vulnerable to flooding in coastal areas and along inland waters. Besides coastal areas, inland waters represent a significant portion of the total land surface in Europe, especially in Italy, the country in Southern Europe with the greatest amount of water resources. According to the European Environment Agency dashboard maps, which include the Copernicus riparian zone dataset, modeled hydrological parameters, and results from the “mapping the world’s free-flowing rivers database” [7], floodplain areas in Europe account for 428,323 km^2, which corresponds to 7.4% of the territory. Such an extensive area involves a floodplain population of 71,360,542, corresponding to 11.7% of Europe's population. The same dashboard provides data on each country. Italy has a floodplain area of 28,885 km^2, equal to 9.7% of the national territory, which involves 13.3% of the population. Both percentages are higher than Europe's average. Most floodplains in Italy are very flat lowlands (12,700 km^2) and flat lowlands (9600 km^2), accounting for more than 77% of the floodplain types.

Regarding the SLR hazard in Italy, Anzidei et al. [2] provided a sea level rise projection for 2100 using an extensive database that included the isostatic and tectonic contribution to the IPCC and Rahmstorf climatic models [8]. The results have shown that by the end of the century, the SLR along Italian coasts is estimated to be between 0.94 and 1.035 m (conservative model) and between 1.31 and 1.45 m (on a less conservative basis). In this context, another current phenomenon is the explosive urban growth progressively challenging the world's cities and megacities, making it increasingly difficult to manage their spatial development in a sustainable way.

Besides mitigation strategies, adaptation strategies are crucial in dealing with coastal erosion, fluvial and coastal flooding, SLR, and building resilient habitats while safeguarding ecological systems. Long-term interactions between adaptation on a local scale and mitigation on a global scale can lead to synergies that contribute to advancing sustainable development in the long term. Climate risks can be reduced by accelerating trans-sectoral and multi-level mitigation interventions in parallel with incremental adaptation actions to foster the transition of current territorial and urban structures towards progressive climate-resilient conditions [9]. The WGII IPCC AR6 Report [10] emphasizes the role of cities as places of increasing vulnerability (population growth) and opportunities for climate adaptation and mitigation action. Broadening the perspective from risk management to creating urban opportunities entails conceiving cities as complex structures consisting of buildings and spaces, an economy, community, infrastructure, and natural environment. Shifting the approach from "defending from water" to "living with water" requires considering the entire urban ecosystem. Currently, responses to flooding, SLR, and land subsidence include a wide range of different types of adaptation strategies [11–13] that can be traced back to four main actions [14–16]:

- Protect to reduce the likelihood of hazards;
- Accommodate by modifying buildings to reduce the impact of the hazard event;
- Retreat (or planned relocation) to reduce exposure by moving away from the source of hazard;
- Advance by creating new land by building seaward, reducing coastal risks for the hinterland and elevated land.

As highlighted by the AR6 IPCC Report, these responses are more effective if combined or sequenced, aligned with sociocultural values, and underpinned by inclusive community engagement processes. Ecosystem-based accommodation solutions such as wetlands provide co-benefits for the environment and climate mitigation and reduce costs for flood defenses, but have site-specific physical limits and lose effectiveness at high rates of SLR beyond 0.5–1 cm/yr. Protection devices like seawalls can effectively reduce impacts in the short term but can also result in lock-ins and increase exposure to climate risks in the long term unless they are integrated into a long-term adaptive plan. Retreat often entails abandoning existing urban assets and communities. Land reclamation is extremely resource-consuming and presents several environmental limitations as it implies the use of fill-in materials that can change, and thus damage, the natural landscape and marine habitats. Floating solutions have been recently officially recognized by the AR6 IPCC Report as an accommodation measure that has already been implemented locally within cities as part of a hybrid strategy, together with protection measures [17,18]. Several studies agree that floating solutions are among the most advisable accommodation measures against SLR regarding sustainability, lifespan, and cost-effectiveness [19–21]. As evidence of this, in the most virtuous European and international contexts, water-based floating development is gaining increasing attention. It is becoming a component of city plans for sustainable development and climate adaptation [22]. The resilience and sustainability of floating solutions are embodied in their intrinsic ability to withstand the effects of climate change (CC) and natural disasters, in the opportunity for spatial development with zero land consumption, and in the feasibility of integrating a circular use of resources, and in the way they offer at the same time a solution for urban development. The inevitably isolated location of water-based architecture makes it the ideal space for applying net zero energy and self-sufficiency principles, as the connection to the terrestrial electricity, water, and sewage networks is not direct. Energy production through active systems such as algae bioreactors, solar panels, wind turbines, and power generators; food production through algae and fish farms and hydroponic agriculture; and water autonomy through desalination are consolidated practices. Oceans are a huge potential source of energy: according to the Global Energy Survey Report, only 0.1% of ocean wave energy is enough to provide five times the world's energy needs [23]. To date, several technologies are being investigated to exploit this potential. These include tidal and marine energy, wave energy, temperature difference, and salinity energy.

As a result, floating cities are emerging as a climate-resilient solution to urban expansion, preventing community displacement in flood-prone areas while aligning with ecological sustainability and urban resilience theories. New urban forms like large-scale floating districts and floating island cities are expected to develop as extensions to coastal cities or as free-floating cities in international waters [24]. Floating city development supports urban resilience by promoting redundant, decentralized infrastructure and reducing dependence on terrestrial networks through autonomous energy, water, and food production systems. Moreover, it allows dynamic, scalable urban expansion to respond to future uncertainties and needs. Several authors agree that floating development represents not only a climate-proof solution for global land shortages and urban population growth but, if integrated with food and energy systems, provides a sustainable urban expansion opportunity for delta and coastal areas, increasing the economic feasibility of floating solutions [22,25,26]. Existing studies on floating urban development focus on regions where floating development is already integrated into urban planning policies (e.g., the Netherlands, Scandinavian countries, or Southeast Asia). Italy lacks a clear regulatory framework for floating urbanism, particularly regarding water zoning, ownership rights, and infrastructure integration. Therefore, existing studies fail to address Italy's specific condition. Existing urban planning regulations in Italy are often rigid, designed for land-based development, and do not adequately accommodate amphibious or floating structures. In addition to this, strict heritage preservation policies and resistance to altering historic waterfronts further challenge adaptation interventions. Moreover, unlike the Netherlands, where floating urbanism thrives due to stable and controlled water systems, Italy has highly diverse and dynamic water bodies, including coastal lagoons, river deltas, and rapidly shifting flood-prone areas.

In Italy, in fact, not all waterfront areas are suitable for accommodating floating urban development on water because of site-specific urban, social, cultural, heritage, infrastructural, climate, and hydrographic features. Therefore, this study aimed to map the areas along Italian waterfronts where the conditions were more favorable for a pilot extension of existing settlements on water. The process of developing, gathering, and evaluating spatial data and information in urban environments, known as urban mapping, is widely used in urban studies to enable the comprehension and management of complex urban environments by providing a multifaceted information layer. This study proposes a novel approach: the application of urban mapping principles to the water environment. This approach hinges on the assumption that urban water bodies are an extension of the terrestrial urban surface.

This paper presents a novel methodology for supporting decision-making on the location identification of future floating urban expansions. By considering integrated benefits and identifying the spatial, infrastructural, and socio-economic parameters for locating future floating urban developments (FUDs), this methodology creates a unique decision support system. This innovative approach not only addresses the challenges of urban expansion but also paves the way for sustainable and resilient future cities.

2. Materials and Methods

The goals of the study are (1) to identify the quantitative/qualitative parameters for analyzing the suitability of waterfront areas for FUD in the Italian territory and (2) to establish the spatial parameters to correctly plan future FUD, maximizing its potential from three different aspects: (a) overcoming CC effects and addressing vulnerable communities, (b) maximizing the energy production potential, and (c) guaranteeing comfortable conditions for permanent inhabitation.

The research methodology is based on comparative analysis and geographic information system (GIS) mapping to find the best locations for floating urban development in Italy, focusing on the water surfaces of waterfront cities and settlements marked by a high vulnerability to sea level rise (SLR) and flood risk. The analysis of waterfront areas is carried out within the boundaries of Italian territorial waters, more specifically in sheltered waters. The mapping is based on a comprehensive evaluation of several variables and location constraints. It aims to identify specific areas marked by the co-existence of environmental and socio-urban needs. GIS technology has allowed the creation of geo-referenced data from a statistical analysis obtained from instrumental measurements, the management and analysis of existing territorial data, the evaluation of patterns and trends in the data, and the aggregate of data from a range of sources (such as satellite images, raster images, and territorial statistics).

The position along the shore for a potential FUD is influenced by two main drivers: vulnerability to CC and development needs (including proximity to a waterfront city). From a strategic point of view, given the need for connection to existing physical and economic infrastructure, floating communities will most likely be located near existing human activity hubs as extensions of existing waterfront cities and settlements. Therefore, a preliminary mapping of Italian coastal areas is carried out to identify Italian waterfront urban areas that are more vulnerable to SLR and flooding and characterized by high-intensity economic, social, and cultural activity levels. The first parameters taken into consideration were as follows:

1. Vulnerability to SLR (SSP5—8.5 by 2100);
2. Vulnerability to flood risk (high- and medium-probability hazard);
3. Intense soil consumption;
4. Proximity to cities or densely populated areas (degree of urbanization);
5. Proximity to high-demographic-concentration municipalities (demography index by municipality).

The elaborated maps were used to pinpoint regions of opportunity. Subsequently, these regions were evaluated and compared against a suite of additional parameters. There is a degree of overlap between locations with potential for human development and locations where natural ecosystems are most affected by human activity. The site selection strategy identifies locations where human and environmental needs resulting from CC and urban growth intersect. From this perspective, environmental constraints are considered, and protected areas are avoided when selecting suitable areas. Site-specific technological and logistic challenges must be considered to simplify and optimize the construction process on the one hand and the accessibility and attractiveness of a new urban development on the other. Relevant factors thus include proximity to strategic transportation infrastructure and distance from intense maritime traffic. Water conditions must be adequate for hosting permanent inhabitation. Wave conditions, water temperature, and water fluctuations were considered to ensure motion comfort and reduce the technical costs for customizing plant cables and pipelines, mooring piles, access facilities, and other technical devices. Finally, a microclimate analysis was conducted to balance energy production potential (solar, wind, water temperature, wave, tidal) with user comfort. For instance, maximizing wave, tidal, or wind energy potential often conflicts with motion comfort, as optimal marine renewable energy generation requires dynamic wave conditions, whereas motion stability demands calm waters (Douglas scale 0, 1, or 2, with maximum wave heights $\leq$ 0.50 m and restricted wave frequencies of 0.18–0.25 Hz to minimize motion sickness).

All things considered, the additional parameters included the following factors:

1. Proximity to strategic transportation infrastructure (seaports, airports, train lines);
2. Microclimate conditions (air temperature, wind speed, relative humidity);
3. Hydrographic conditions (wave height, current speed, water fluctuations, water temperature, water quality);
4. Energy production potential (sun, wind, wave height, current speed, salinity);
5. Environmental constraints (Natura 2000 areas).

The geospatial analysis has been developed in a GIS environment (QGIS Open Source) by combining the use of several available European, National, and Regional open-source datasets listed in Table 1.

Table 1. Data types and sources used for the geospatial analysis.

Data Field	Dataset	Source	Data Type *
Urban (priority parameters)	Degree of urbanization	Elaboration using data from ISTAT census 2011	Vector
	Demographic index by municipality	Elaboration using data from ISTAT census 2023	Vector
Urban (additional parameters)	Transportation infrastructure	Geoportale nazionale (MASE) + areoporto.net	Vector
	Micro-climate conditions	ISPRA RON (Rete Ondametrica Nazionale) 2023	Spreadsheet
	Hydrographic conditions	ISPRA RON (Rete Ondametrica Nazionale) 2023	Spreadsheet
	Water contamination	European Commission Emodnet geo-database	Vector
	Energy production potential	Elaboration using data from Maestrale EU Interreg MED 2014–2020	Raster
	Rete Natura 2000 areas	Geoportale Nazionale (MASE)	Vector
Risks	SLR risk areas: land below annual flood level in 2100 (SSP5.8.5)	Climate Central (https://coastal.climatecentral.org/ accessed on 20 November 2024) based on SSP5-8.5 (IPCC 2021)	Vector
	Flood risk classes	ISPRA (Floods Directive 2007/60/EC)	Vector
	Coastal city inundation	CReSIS 2018	Vector
	River flooding (2071-2100) 1 in 100 years return period	EEA database Datasets (UMZ from Urban Atlas 2012 and LISFLOOD model outputs from JRC)	Vector
Land use	Soil consumption	ISPRA 2022 [27]	Vector

* All vector datasets have been reprojected in the same CSR (WGS 84/UTM zone 32N EPSG:32632) to allow geoprocessing tools.

Ultimately, a comparative analysis was carried out to systematize and evaluate the pros and cons of each potentially suitable area.

Other authors in different disciplinary fields have applied similar research approaches. To name a few, Martinez et al. [28] have applied a similar mapping method for the identification and selection of sites in Ireland for floating offshore wind systems, while Gola et al. [29] have developed and implemented a research method for mapping suitable areas for locating community healthcare facilities in Italy.

The proposed methodology and findings directly support climate-resilient coastal urbanization, aligning with the UN Sustainable Development Goals on sustainable cities, clean energy, and climate action, by addressing the interconnected challenges of climate change adaptation, urban expansion, and environmental preservation. Indeed, FUDs offer a sustainable adaptation strategy by expanding urban areas without increasing land consumption, while reducing displacement risks for coastal populations.

3. Results

3.1. Vulnerability and Urban Demographic Concentration

In the Italian region, rapid urbanization started after the 60s of the 20th century, leading to the uncontrolled expansion of coastal settlements, which today are exposed to increasing coastal hazards [30]. Land consumption, defined as the shift from non-artificial land cover to artificial land cover [31], which is associated with the loss of ecosystem services, is another essential aspect to consider when identifying areas that are more eligible for consideration in applying the shift from land to water for urban purposes. The map in Figure 1, elaborated using data provided by ISPRA [27], shows the percentage of soil consumed at the communal level. The orange-red areas experienced more than 9% of soil consumption in 2022. Cities like Milan, Turin, Naples, Bari, and Palermo have experienced more than 30% of soil consumption, followed by Rome and its surrounding municipalities, Venice, Catania, the Tuscan coast, and the Pianura Padana areas around Modena, Parma, and Bologna, ranging from 15 to 30% of soil consumption.

The dark blue circles pinpoint the Urban Morphological Zone (UMZ) potentially at risk of river flooding (1 in 100 years return period), modeled for 2071-2100. The data are taken from the EEA database Datasets, which used the UMZ from Urban Atlas 2012 and LISFLOOD model outputs from the JRC. The resultant modeled flood area was intersected with the extent of the UMZ, and the proportion of potentially flooded UMZ area was calculated for each city by dividing the potentially flooded area by the total UMZ area. It is essential to highlight that the indicator is based on elevation and does not include existing or planned flood protection measures like dams or dikes. In the highlighted areas, the percentage of flooded territory ranges from 0.03% in Sassari (Sardinia) to 45% in Padova. Taking a closer look at the areas that overlap with soil consumption, it is crucial to point out Milan with 13 + 5% of the UMZ extent, Florence with 13%, Turin with 9%, Rome with 4.4%, Modena with 10.2%, Forlì with 6.5%, Bologna with 2%, Ravenna with 23%, Bari with 6.1%, Catania with 16.8%, and Pisa with 10.6%. The violet circles identify the areas facing coastal inundation risk. The map shows the coastal cities exposed to inundation by a SLR of 1 m (without any coastal flooding defenses present). The SLR dataset used for the map was developed by CReSIS (Center for Remote Sensing of Ice Sheets) in 2018. To no surprise, coastal inundation tends to match with river flooding risk projections, as both are exacerbated by CC. SLR is the primary driver of coastal inundation, while increased precipitation is the leading cause of river flooding. In addition, coastal areas are often located in low-lying areas where rivers also tend to flow, making them more susceptible to flooding. Moreover, most of the areas at risk of coastal inundation are often located at the deltas of rivers (i.e., Rome is on the Tiber River, Venice is immediately above the River Adige delta, the River Po and its delta crosses the area between Venice and Ravenna, and the area above Livorno is located on the delta of the River Arno).

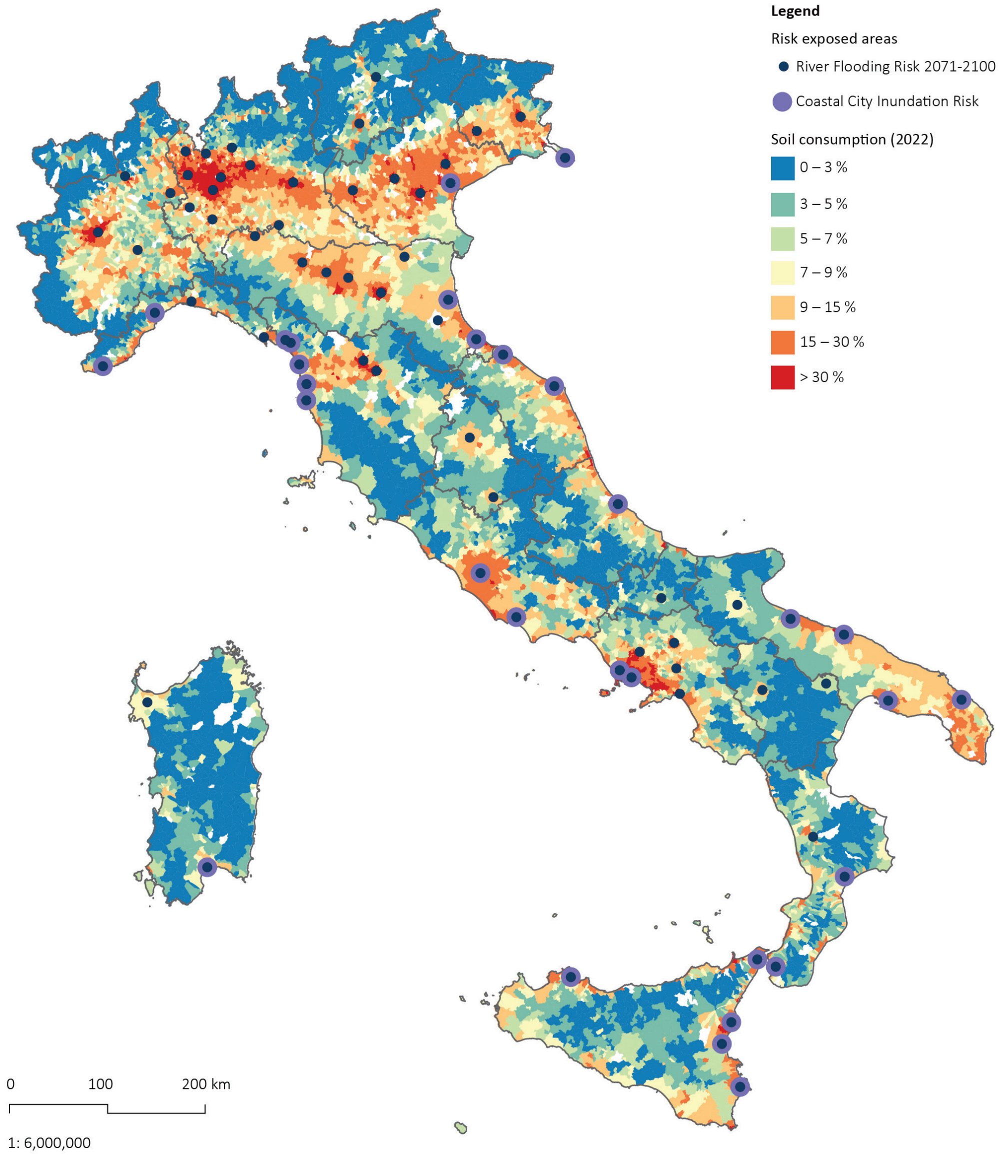

Figure 1. Soil consumption (2022) related to risk exposure in terms of river flooding and coastal city inundation (2071–2100). Source: Livia Calcagni.

A numerical analysis of the transformation of over 8000 km of the Italian coastal area within the last forty years—reconstructed by processing satellite images and maps—revealed that 3291 km, corresponding to 51% of the Italian coastal landscape, was modified between 1988 and 2012 [27]. Despite the limits imposed by Law 431/1985, an additional 41,000 m of coastal terrain has been irreversibly transformed since 1985. In general, the transformation of the coast has taken place at the expense of beaches, dunes, and natural green areas, but above all, at the expense of agricultural land. Calabria, Liguria, Lazio, and Abruzzo have a poor track record, with only one-third of the natural environment preserved, while the rest is contaminated and occupied by ports and buildings. Uncontrolled coastal urban development led to unsustainable overexploitation of fragile ecosystems, resulting in a total of 302 km of coastline being transformed. These numbers correspond to 13 km per year or 48 m per day. The most severe situation occurred in Sicily, where 65 km had been transformed. However, the condition in Lazio is also severe, with 41 km of natural and agricultural landscapes erased by concrete, and in Campania with 29 km.

Mapping demographic distribution instead of land consumption provides information on the vulnerability of the different areas regarding the risk of loss of life, property damage, and economic disruption. Understanding population distribution is essential for informed urban planning and urban development decisions. The map in Figure 2 depicts the overlapping population distribution and flood risk. The red gradient shows the population distribution by municipalities: dark red areas have high demographic numbers. The data are taken from the ISTAT census 01/01/2023. The blue-gradient category returns three levels of flood risk:

1. Low-probability hazard (LPH)—300 years;
2. Medium-probability hazard (MPH)—100 years;
3. High-probability hazard (HPH)—20–50 years (or extreme event scenario).

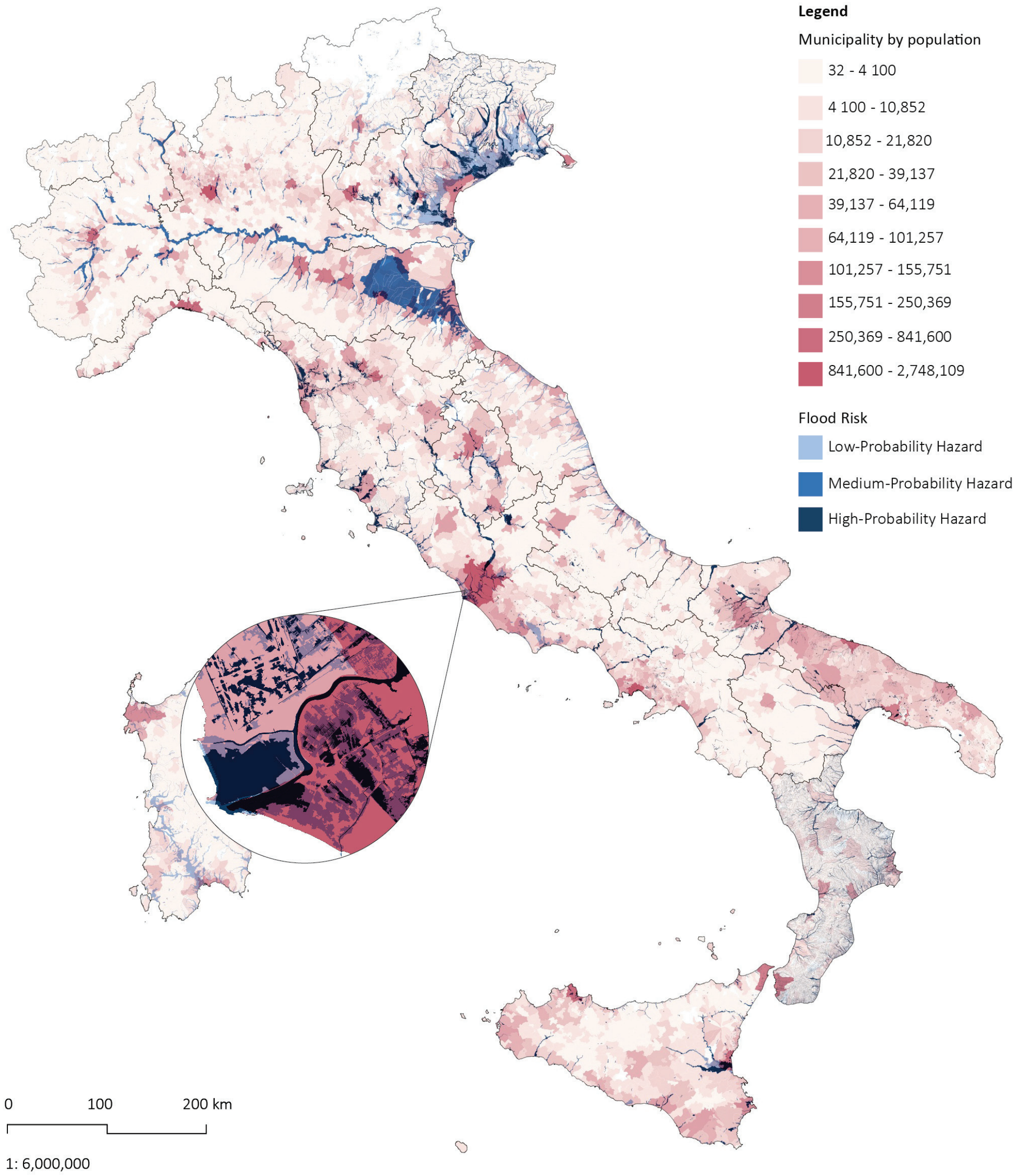

Figure 2. Map of flood risk in Italy overlapped with population distribution by municipality. Source: re-elaboration by Livia Calcagni using data from ISTAT census 01/01/2023 and ISPRA according to Floods Directive 2007/60/EC.

The data behind the potentially floodable areas are produced by ISPRA and are consistent with Floods Directive 2007/60/EC. Legislative Decree 49/2010, implementing the Floods Directive, establishes that scenarios of high probability or frequent floods are those corresponding to return times between 20 and 50 years (e.g., for the scenario c = Tr $\leq$ 30 years), while scenarios of medium probability or infrequent floods are those corresponding to return times between 100 and 200 years (e.g., for the scenario b = Tr $\leq$ 150 years). Those related to return times exceeding 200 years are considered low-probability or extreme event scenarios (e.g., for the scenario a = Tr $\leq$ 300 years). The extent of the floods should be understood as the entire surface covered with water in the event of a specific scenario (therefore not excluding the riverbed).

The map highlights the areas that are densely populated and, at the same time, face a more significant flood risk. The Po Valley is not so densely populated but is subject to medium-probability hazards for a considerable extent of its territory. In terms of extension, the areas around the Tiber delta in the Municipality of Rome and Fiumicino, the northern part of the Puglia region (Foggia Province), the city of Catania, and the coastal areas between La Spezia and Livorno are far less impacted. However, the risk is higher (high-probability risk). These areas also host a higher number of inhabitants.

Leaving aside urban population in terms of demographic distribution, urban densification in the consolidated city and sprawling phenomena on fringe and rural areas have become a matter of investigation [30,32,33]. It is even more compelling to compare and overlap flood risk with the degree of urbanization, as shown in the map in Figure 3.

This correlation is even more critical because if a region's demography is high, it is not necessarily growing. The orange gradient scale returns three degrees of urbanization:

1. Cities or densely populated areas;
2. Small cities and suburbs or intermediate population density areas;
3. Rural or scarcely populated areas.

The blue-gradient areas represent, once again, the flood risk areas. Compared with the previous map (population by municipality and flood risk), the areas of interest—affected by both phenomena—are almost the same. This implies that the most densely populated municipalities also have the highest degree of urbanization in this case.

The maps in Figures 4 and 5 provide information, respectively, on the co-existence of SLR projections and demographic distribution and of SLR and degree of urbanization. Therefore, the same map containing information on the degree of urbanization for Italian municipalities was superimposed on the risk of SLR. The map in Figure 4 represents the areas most subject to SLR with forecast scenarios for 2100 and their relation to demographic distribution. The map in Figure 5 shows the areas most subject to SLR with forecast scenarios for 2100 and their association with degree of urbanization. The forecast data are calculated considering the SSP5-8.5 scenario, according to which annual emissions will approximately double by 2050. The parameters considered for SLR projections include the following set-ups inserted in the Coastal Risk screening tool developed by Climate Central.

- SLR + annual flood: local sea level projection plus the added height of a local annual flood. The sea level projection source is the IPCC 2021;
- Current pollution pathway trajectory: SSP5-8.5;
- Mid-range result from sea level projection range (50th percentile);
- Threatened areas shown include all land below water level.

In both maps, the areas in the light blue grid hatching are predicted to be submerged by water by 2050 according to the SSP5-8.5 scenario, while those marked in blue hatching are expected to be submerged by 2100.

Along the Northern Adriatic coast, the territory of the lower Po Valley (n°4), right near the mouth of the River Po, is undoubtedly the Italian area with the greatest risk of being submerged. Forecasts for 2100 show an area extending to over 40 km inland, almost reaching the city of Ferrara. The area affected by the phenomenon involves the provinces of Rimini, Ravenna, Ferrara, Rovigo, and Venice.

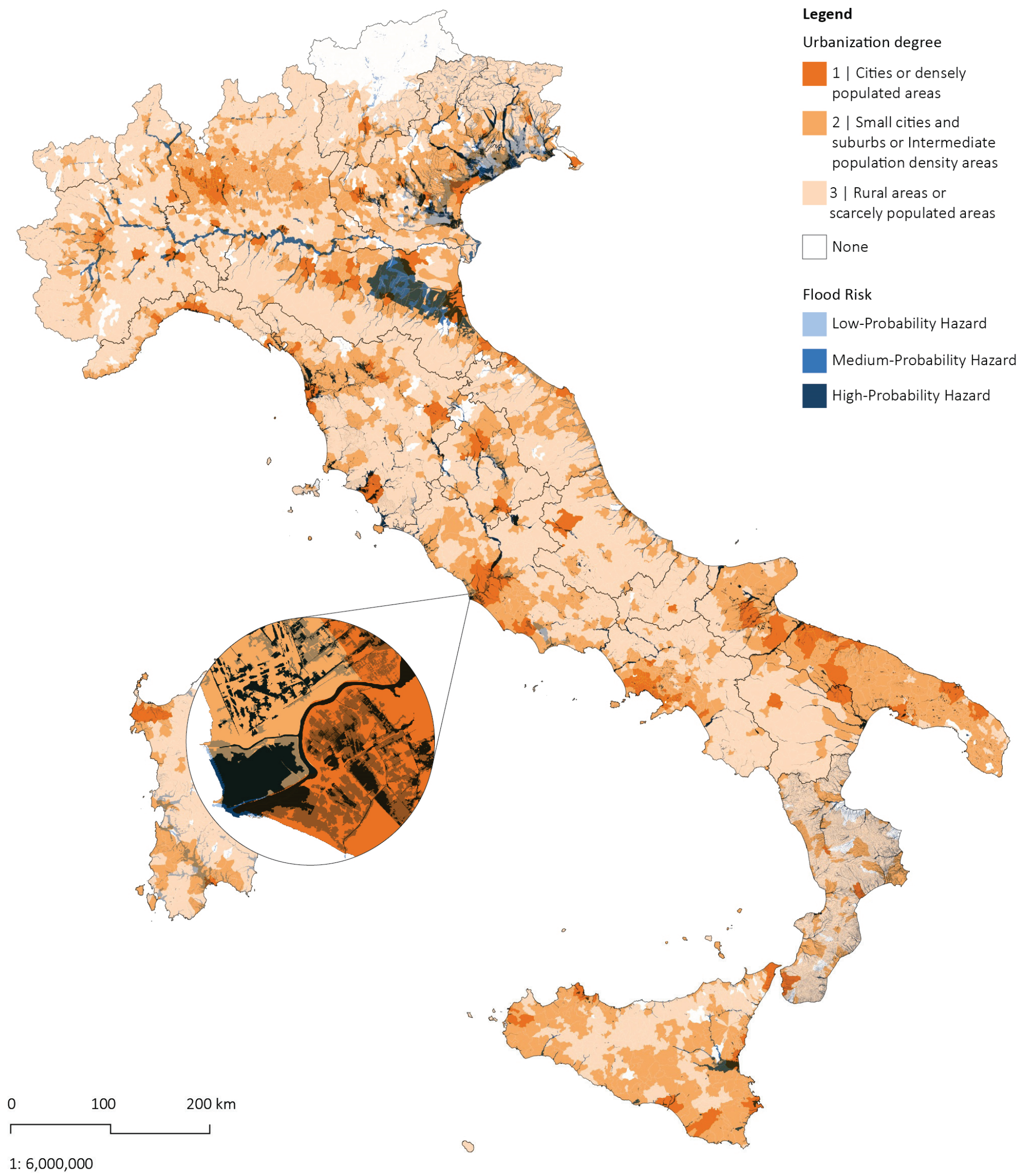

Figure 3. Map of flood risk in Italy overlapped with degree of urbanization. Source: re-elaboration by Livia Calcagni using data from ISTAT census 2011 and ISPRA according to Floods Directive 2007/60/EC.

The area within the Province of Foggia and the Province of Barletta (n°6) will already be submerged by water in 2050 and to a greater extent by 2100. The municipalities affected by the phenomenon are Fiumara, Margherita di Savoia, Trinitapoli, Setteposte, Zapponeta, Ippocampo, Scalo dei Saraceni, Scali degli Zingari, and Siponto. The internal areas affected by flooding by 2100 are located more than 4 km from the current coastline.

Shifting to the Northern Tyrrhenian coast, the Province of Livorno (n°1) is highly affected by the SLR, especially the area around Marina di Pisa, located at the mouth of the River Arno, Calambrone, and Tirrenia. The internal areas affected by the phenomenon by 2100 are almost 4 km away as the crow flies from the current coastline.

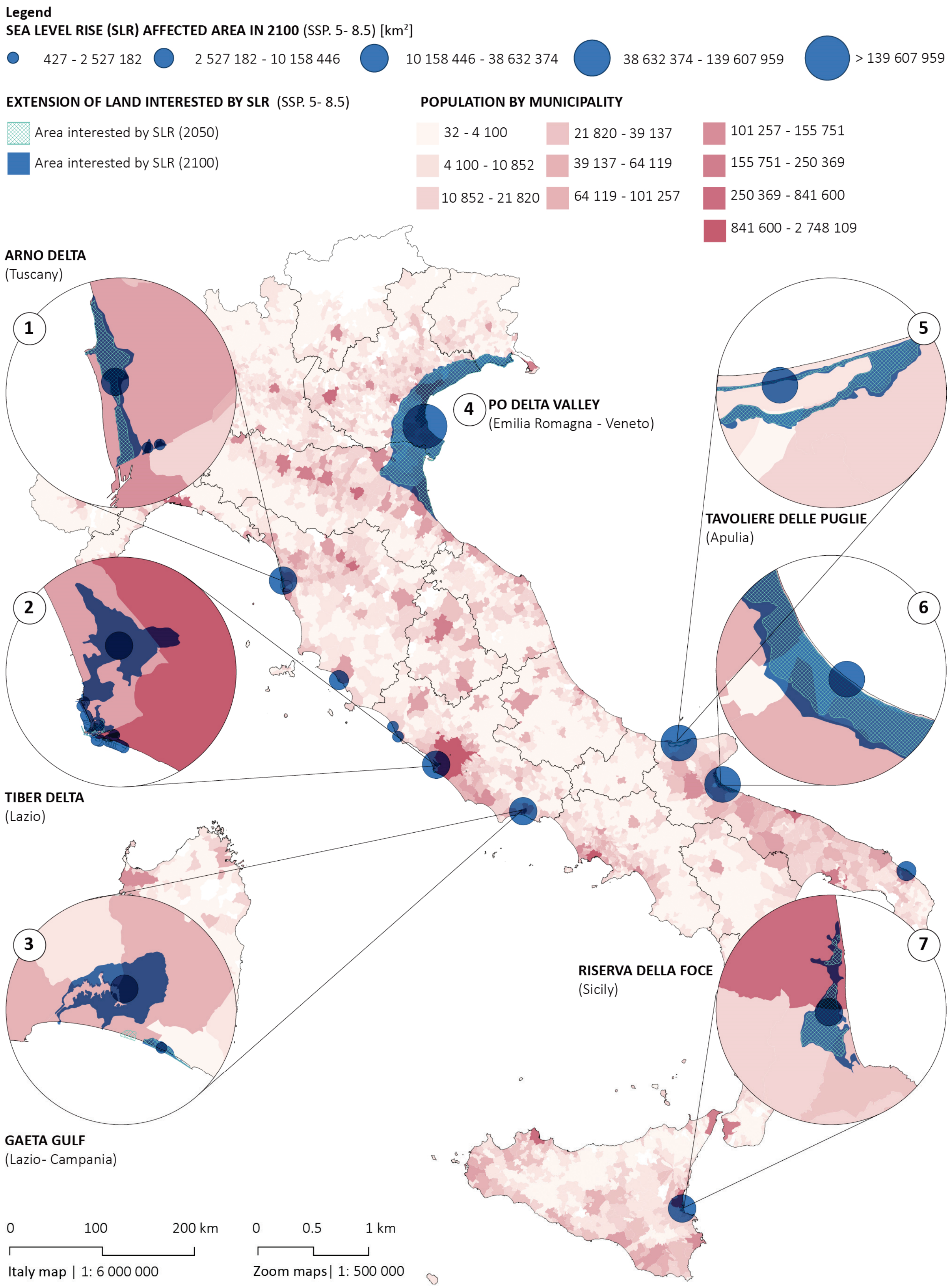

Figure 4. Map of sea level rise projections by 2100 (SSP.5-8.5) in Italy overlapped with demographic distribution by municipality. Source: re-elaboration by Livia Calcagni using data from ISTAT census 01/01/2023 and Climate Central Coastal Risk (IPCC 2021, SSP5-8.5).

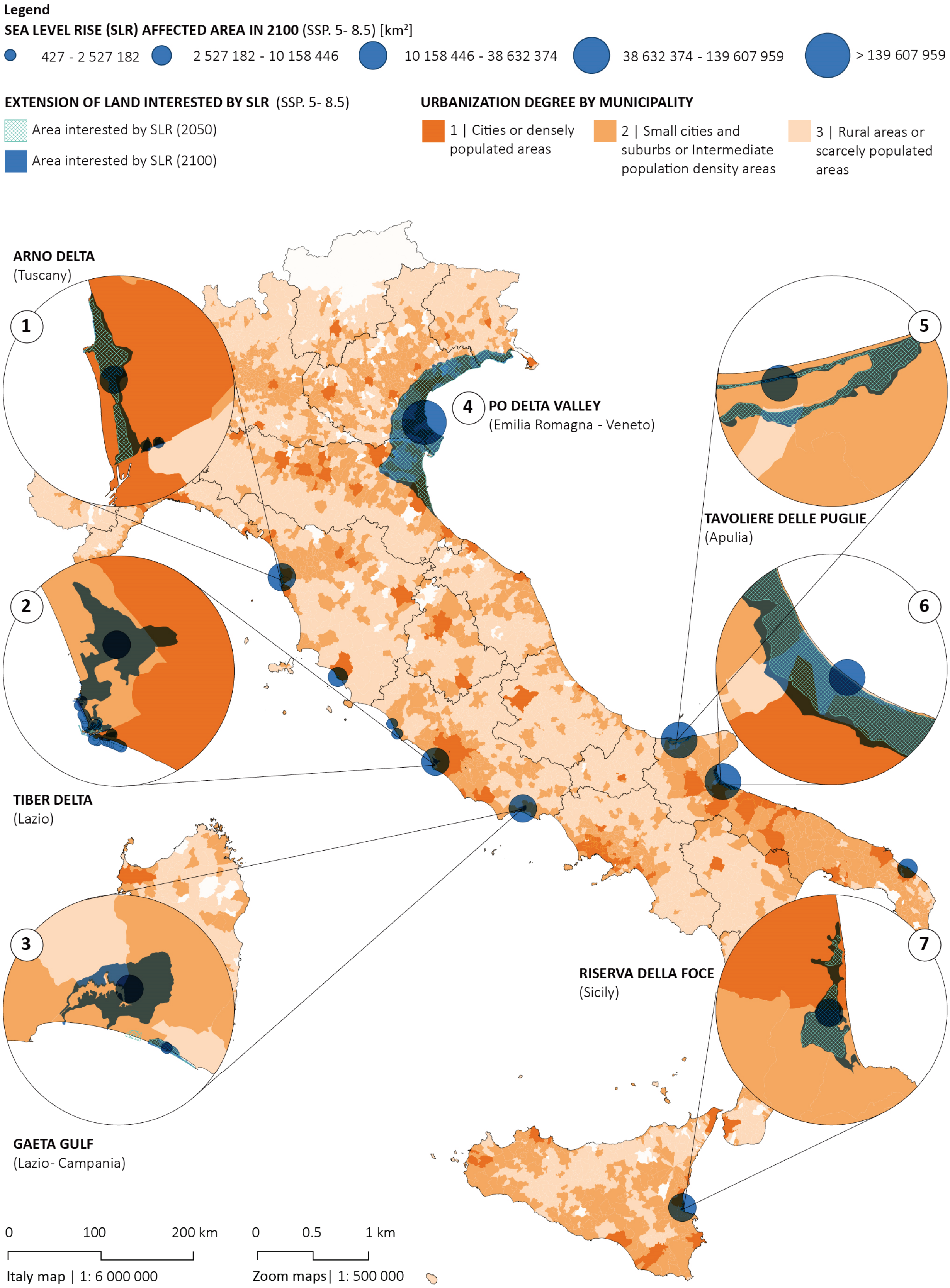

Figure 5. Map of sea level rise projections by 2100 (SSP.5-8.5) in Italy overlapped with degree of urbanization. Source: re-elaboration by Livia Calcagni using data from ISTAT census 2011 and Climate Central Coastal Risk (IPCC 2021, SSP5-8.5).

Moving south, predictions of SLR involve the entire hamlet of Isola Sacra and a good part of the area currently used as the infrastructure of the Leonardo da Vinci International Airport (Municipality of Fiumicino), portions of Ostia and Piana del Sole (Municipality of Rome), and up to 200 m of areas adjacent to the Tyrrhenian coastline that stretches from Fiumicino towards Civitavecchia in the Province of Rome (n°2). The internal territory affected by the phenomenon by 2100 will reach more than 9 km of inward land from the current coastline.

Further south, the Gulf of Gaeta (n°3) is also affected by the phenomenon, especially Sperlonga town and the stretch of land between the coast and the municipality of Fondi.

In Sicily, the most vulnerable area to SLR is located south of the Simeto River's Pineta della Riserva della Foce in the Province of Catania (n°7). It includes the municipality of Vaccarizzo-Delfino and some further southern areas of Catania metropolitan city. The phenomena also affect some parts of the Province of Syracuse, such as Villaggio San Leonardo.

Ultimately, it is crucial to mention the speeding up of the erosion phenomena, especially along the Italian coasts [34]. Unauthorized development and the inadequacy of mitigation techniques and technology have increased erosive stress and unsettled landscapes. The deep artificialization of the coast, or rather the disruption of natural coastal dynamics, has triggered erosion. Advance strategies such as land reclamation or beach nourishment have been implemented, along with protection measures.

This preliminary mapping has led to the identification of six main zones of interest (areas 1, 2, 3, 4, 6, and 7 in Figure 5) that have been further studied concerning the abovementioned additional variables and extensively described in the following paragraph.

3.2. Additional Variables

3.2.1. Proximity to Strategic Infrastructure

For a new urban development to be successful, it must be attractive to new residents. First of all, it must be accessible and within reach by public transport connections by air, water, and land. Therefore, proximity to strategic transportation infrastructure (seaports, airports, train lines) was considered essential for selecting appropriate locations for FUD. Easy access to transportation allows for the movement of people and goods, which is vital for a functioning city, increases the attractiveness of a city, and strongly affects logistics in construction. However, the selected site must be positioned out of the way of intense maritime traffic routes to reduce the risk of collisions with large vessels and ensure better motion comfort. The map in Figure 6 shows the distribution of airports, seaports, and train stations in the national territory, providing information on the mobility quality of the six zones.

The area around Livorno (1) has a station within 5 km of reach, two seaports, and an airport within 10 km. The area between Fiumicino and Rome (2) has several train stations within 5 km of reach, a seaport within 10 km, and an airport within 20 km. The area in front of Gaeta (3) has several ports within less than 5 km, a train station within 10 km, and an airport within 100 km. The area around the River Po delta (4) has a station within 5 km of reach, a seaport 10 km distant, and an airport at around 70 km. The areas in the Province of Foggia (5 and 6) are not accessible by train station, as the closest train station is more than 20 km away. The closest seaport is within 15 km, and the closest airport is 100 km away. The area in front of Catania (7) has a train station, a seaport, and a port within 10 km of reach.

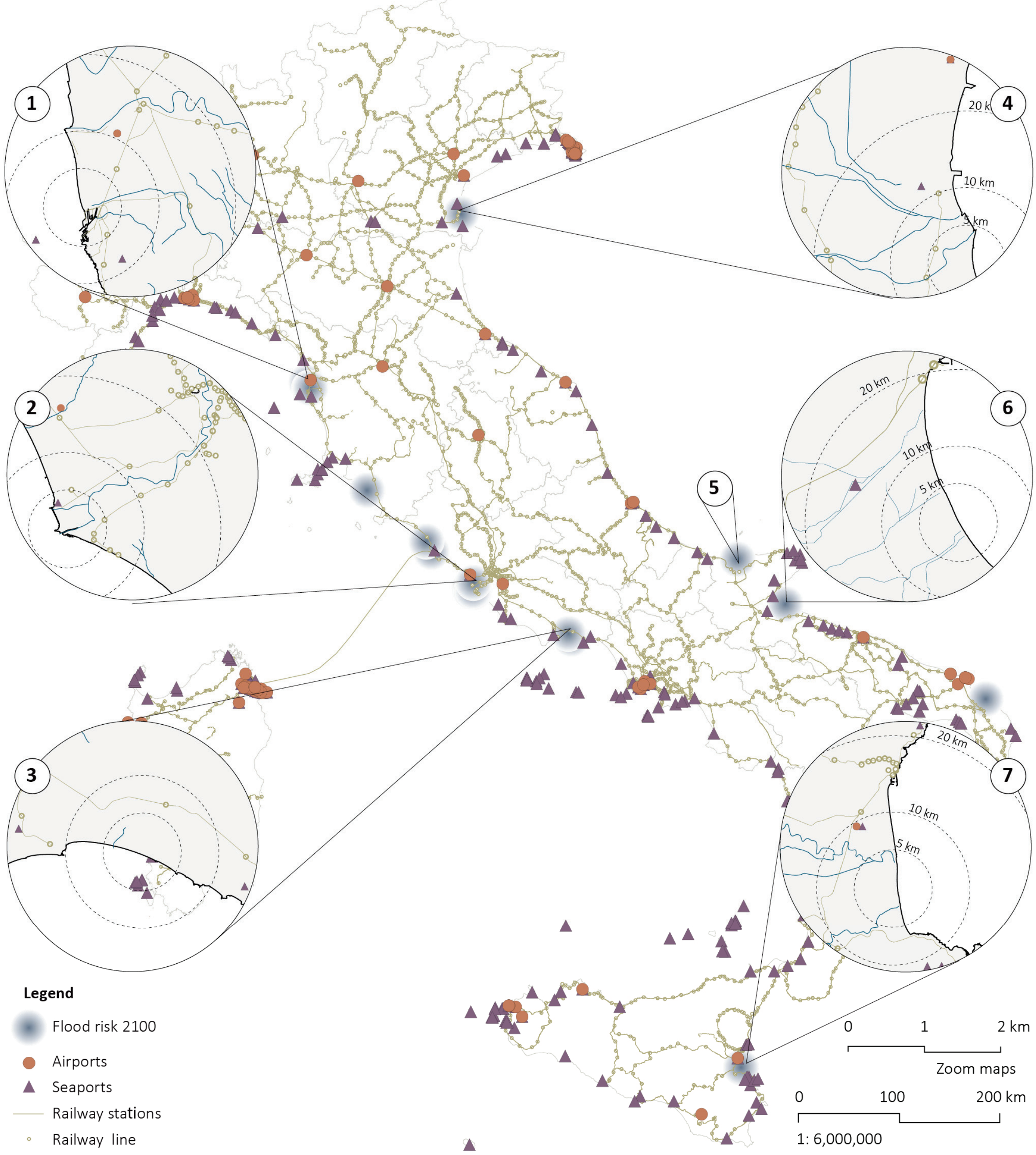

Figure 6. Strategic transport infrastructure proximity (airports, seaports, train stations). Source: re-elaboration by Livia Calcagni using data from areoporto.net and from the Italian Ministry of Environment and Energy Security (MASE).

3.2.2. Environmental Constraints

As argued in the introduction, FUD can only be sustainable if its impact on existing ecosystems is minimized. The mapping involved identifying Natura 2000 areas designated for protecting habitats and species, which, therefore, FUD should avoid disrupting. Among the six identified areas, waters covered by Natura 2000 protection constraints (Figure 7) include the waters around Livorno (1) and some areas along the Po delta (5), both listed as Sites of Community Importance (SICs), and a Special Conservation Area (ZSC) along the coast of Gaeta (3).

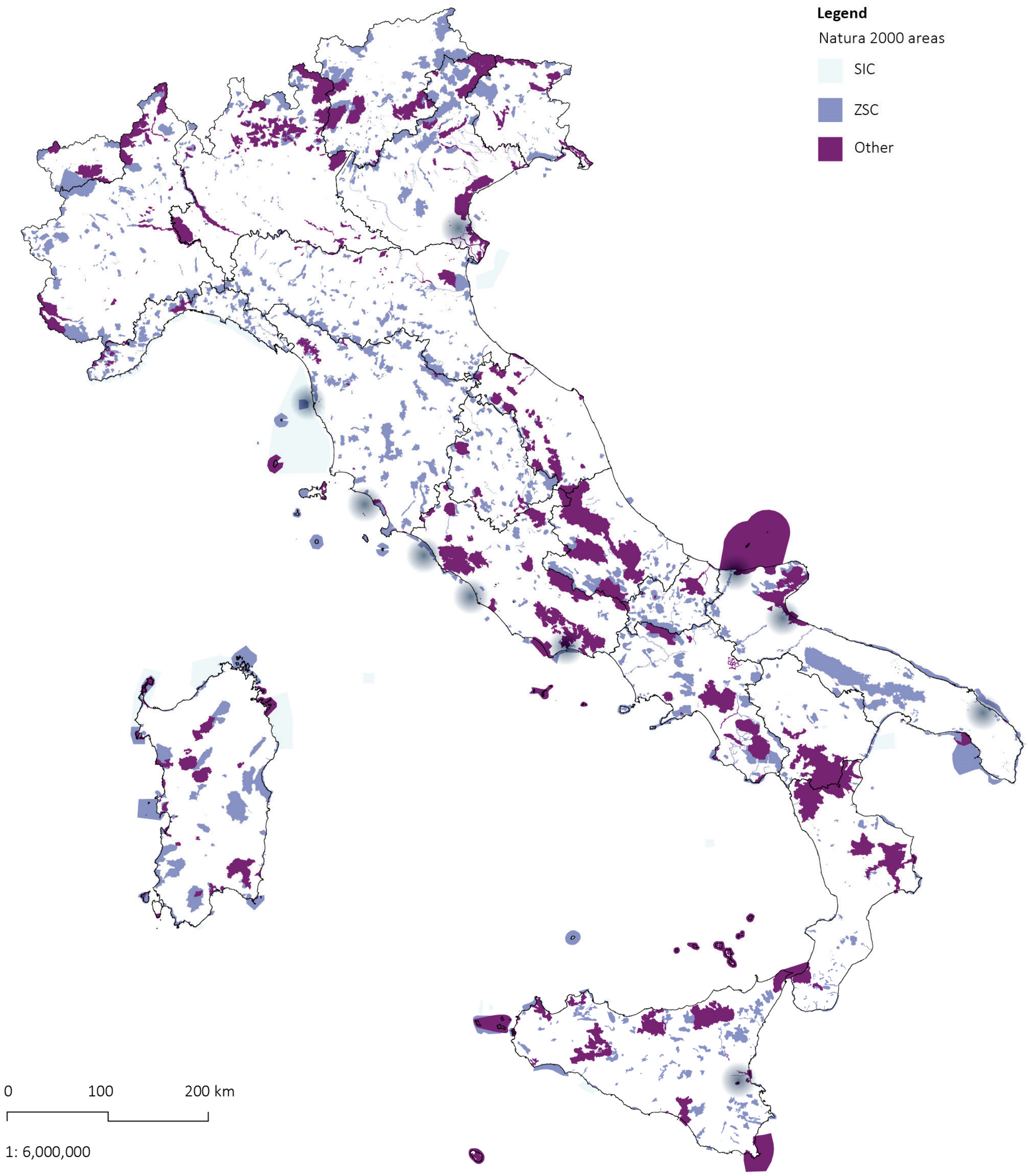

Figure 7. Natura 2000 areas (SICs, ZSCs). Source: re-elaboration by Livia Calcagni using data retrieved from the Italian Ministry of Environment and Energy Security (MASE) for UTM zone 32 N and 33 N.

3.2.3. Water Quality

Water quality was also considered, especially regarding water contamination from hydrocarbons, heavy metals, and pesticides. Median values for anthracene, benzo(a)pyrene, fluoranthene, tributyltin, mercury, lead, cadmium, nickel, and hexachlorobenzene were extracted, normalized (Table 2), and compared (Figure 8).

Figure 8. Water chemical contamination from hydrocarbons (IPA), heavy metals, and pesticides. Source: re-elaboration by Livia Calcagni using data from the European Commission Emodnet geo-database.

Table 2. Comparative analysis of the different potential sites for FUD according to specific parameters; value (V); score (S).

Contaminant	V	S	V	S	V	S	V	S	V	S	V	S
Anthracene [μg/L]	>0.1	1	<0.1	3	>0.1	1	>0.1	1	<0.1	3	>0.1	1
Benzopirene [μg/L]	>0.027	1	<0.027	3	>0.027	1	>0.027	1	<0.027	3	>0.027	1
Fluoranthene [μg/L]	>0.12	1	<0.12	3	>0.12	1	>0.12	1	<0.12	3	>0.12	1
Tributyltin [μg/L]	>0.0015	1	>0.0015	1	>0.0015	1	>0.0015	1	<0.0015	3	<0.0015	3
Mercury [μg/L]	>0.07	1	<0.07	3	>0.07	1	>0.07	1	<0.07	3	>0.07	1
Lead [μg/L]	>14	1	<14	3	>14	1	>14	1	<14	3	>14	1
Cadmium [μg/L]	>0.45	1	>0.45	1	>0.45	1	<0.45	3	<0.45	3	>0.45	1
Nikel [μg/L]	>35	1	<35	3	>35	1	>35	1	<35	3	>35	1
Pesticides [μg/L]	>0.05	1	<0.05	3	>0.05	1	>0.05	1	<0.05	3	>0.05	1

Concerning surface waters, Directive 2008/105/EC of 16 December 2008 establishes environmental quality standards (EQSs) for 33 priority substances identified in the context of Directive 2000/60/EC of 23 October 2000 (Water Framework Directive). The concentration limits listed below are expressed as a maximum allowable concentration (SQA-CMA): anthracene: 0.1 μg/L; benzo(a)pyrene: 0.027 μg/L; fluoranthene: 0.12 μg/L; tributyltin: 0.0015 μg/L; mercury: 0.07 μg/L; lead: 14 μg/L; cadmium: 0.45 μg/L; nickel: 34 μg/L; pesticides (hexachlorobenzene) (0.05 μg/L).

3.2.4. Hydrographic Conditions

Data on the hydrographic level were extracted from the same database and used to evaluate and compare the water level fluctuations in each site (Figure 9). As shown in Graph 2, the highest water level fluctuation occurs in Venice (nearest buoy to area 4), where it reaches 1.03 m, followed by the Tremiti tide gauge (near area 6) and the Ravenna tide gauge (near area 4). The closest buoy to area 1 is the Livorno tide gauge, which registers a water level fluctuation of 0.81 m. The lowest water level fluctuation is registered by the buoy in Civitavecchia (0.57 m) near area 2. The other buoys register a water level fluctuation between 0.59 and 0.66 m.

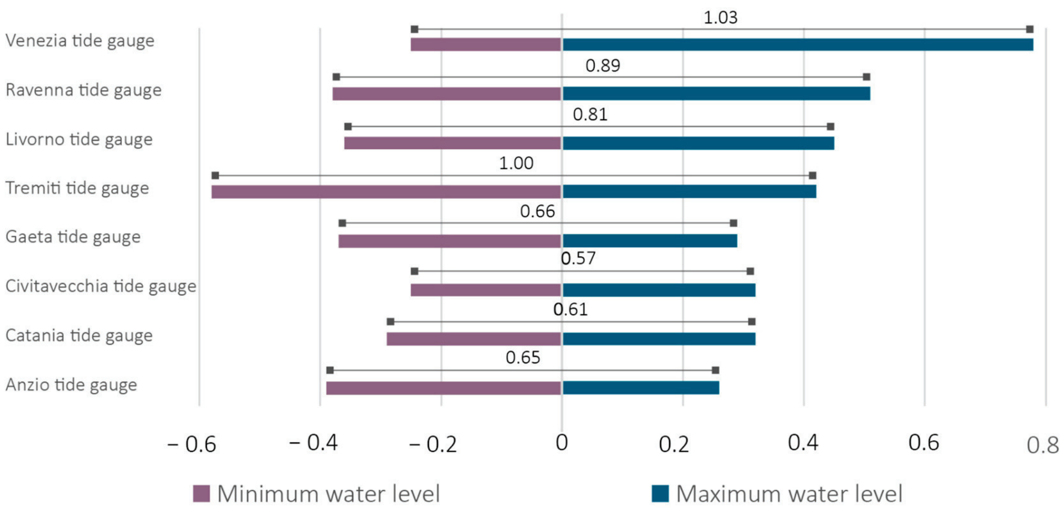

Figure 9. Water level fluctuations registered by the buoys of the RON (Rete Ondametrica Nazionale) in 8 stations.

3.2.5. Microclimate Conditions

Microclimate conditions (air temperature, wind speed, humidity) were analyzed to compare the different sites (Figure 10). The microclimate parameters were deliberately taken from the tide gauge stations and meteorological wave buoys instead of terrestrial climate detection stations because microclimate conditions like humidity and temperature are strongly affected by the water underneath.

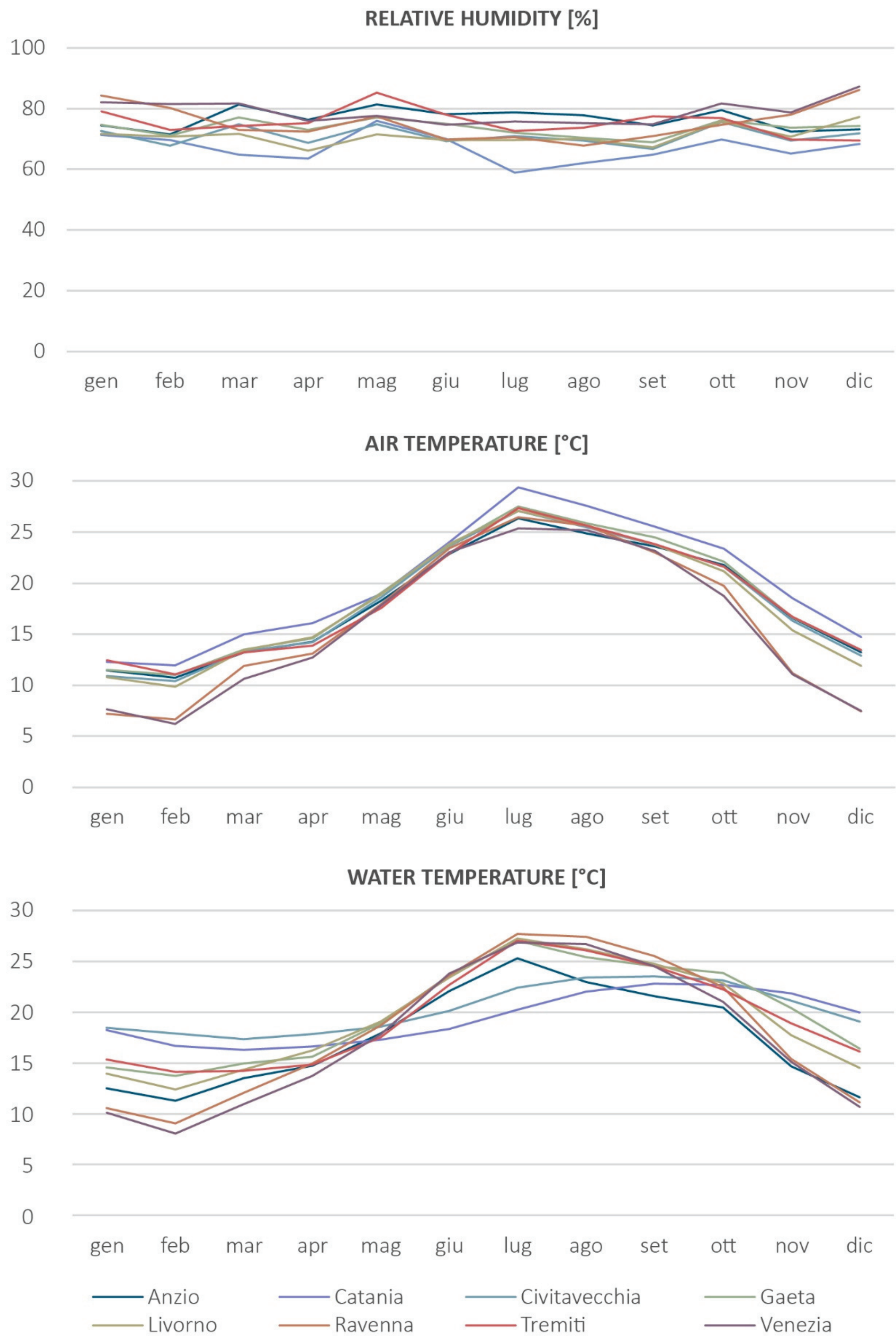

Figure 10. Water temperature, air temperature, relative humidity comparison. Data registered by the buoys of the RON (Rete Ondametrica Nazionale).

Data were extracted from the Rete Ondametrica Nazionale (RON) database for the year 2023. The accelerometer buoys that make up the national network managed by ISPRA represent an essential source of real-time meteorological data on wave height and direction and are freely accessible. Maximum humidity values are registered in the Tremiti buoy (area 6) and Ravenna (area 4), while minimum humidity values are registered in Catania (area 7) and Livorno (area 1). Regarding air temperature, the highest temperatures are registered in Catania (area 7) and the minimum ones in Ravenna (area 4). Water temperature range averages are similar in each buoy station, with low peaks in Anzio (area 2), Ravenna, and Venezia (area 4), yet never under 5 °C.

3.2.6. Energy Potential

Finally, the energy production potential (sun, wind, wave height, salinity, currents) was analyzed to determine the better locations for implementing self-sustaining communities (Figure 11). However, the choice of maximizing energy production entails reducing motion comfort. Therefore, a trade-off and a balance between the two should be pursued. Generally, the Adriatic coast has lower wave interannual mean heights ranging between 0.3 and 0.5 m for a greater extent than the Tyrrhenian coast; however, the interannual mean wave height does not exceed 0.6 m along the entire Italian coast. The interannual mean current speed ranges between 0.01 m/s and 0.04 m/s along the coast. Some waters (area 1, area 3, area 6) are located in more protected areas where the current speed average does not exceed 0.01 m/s all year. Salinity interannual mean levels (measured at a maximum depth of 5 m) are highly different across regions: area 4 has very low salinity levels (36.33 psu) along the coast, while area 7 reaches 38.66 psu. Average salinity mean levels are registered along the entire Tyrrhenian coast and area 6 (38–38.33). Global solar horizontal irradiation is quite similar across the entire coast, with higher levels when moving south: area 2 (1643.5 kWh/m^2), area 7 (1769.3 kWh/m^2), and area 6 (1591.1 kWh/m^2). The same applies for the specific photovoltaic power output: area 2 (1578.6 kWh/kWp), area 7 (1627.1 kWh/kWp), and area 6 (1498.9 kWh/kWp). Mean wind speed is exceptionally high in area 1 (6.29 m/s) and area 2 (6.32 m/s) and between 4.5 and 5 m/s in the other areas.

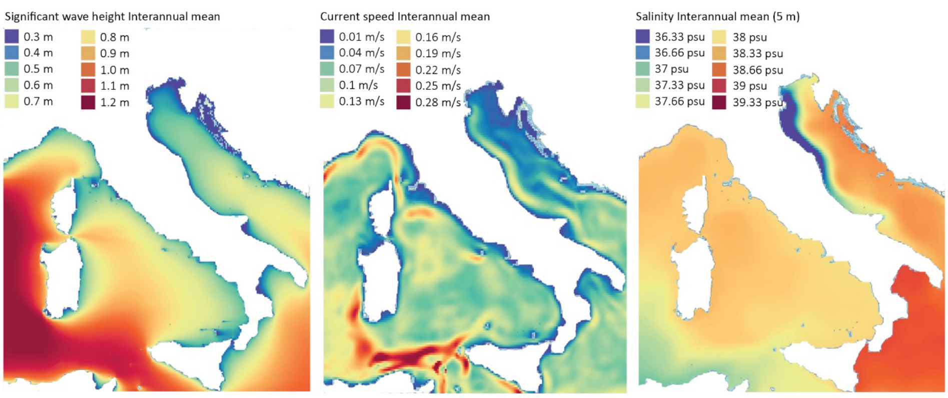

Figure 11. Energy potential parameters (wave height, current speed, and salinity) along Italian waterfronts. Source: re-elaboration by Livia Calcagni using data retrieved from webGIs portal developed within Maestrale EU Interreg MED 2014–2020.

4. Discussion

A comparative analysis, a crucial tool in the decision-making process, was conducted to compare the different sites across all parameters. This method was considered suitable for dealing with multiple, and sometimes conflicting, factors. In this study, each parameter is assigned a weight according to its relative importance, based on stakeholder requirements. It is important to mention that stakeholders could prioritize different aspects based on economic, social, and environmental objectives, leading to variations in site rankings. For example, if the priority is to minimize user motion and ensure thermal comfort, this aspect might be given more weight than maximizing energy production. Alternatively, if urban developers prioritize economic feasibility and accessibility, proximity to transportation infrastructure might receive the highest weight. Conversely, environmental agencies may prioritize minimal ecological disruption, favoring sites with lower contamination and fewer protected areas.

Normalization Process and Comparative Analysis

The raw data for each criterion were in different units. To address this, the comparative analysis employed a normalization process. This process converts the value (V) for each criterion into a scale of scores (S) ranging from 1 to 3. This allows for a fair comparison across all criteria. A score of 1 indicates the least favorable option for that criterion, while a score of 3 represents the most favorable option.

Table 3 represents the comparative matrix developed to systematize and set against all potential sites. Considering the normalized scores, the matrix generates a final ranking or shortlist of the most suitable sites for FUD. Specific rules were established in order to assign a score to each parameter. Flood risk (high, medium, low) was easily converted to a scale from 1 to 3. The same applies to the degree of urbanization. Proximity to infrastructure was converted based on the following distances: airport <5 km = 3, 5–50 km = 2, >50 km = 1; seaport <5 km = 3, 5–10 km = 2, >10 km = 1; train station <5 km = 3, 5–10 km = 2, >10 km = 1. Water contamination was simplified to above (1) or below (3) limits, and an average of all contaminants was calculated for each site. Environmental constraints were converted to a binary variable: yes = 1; no = 3. Average water fluctuation was converted as follows: <0.7 m = 3; 0.7–0.81 m = 2; >0.82 m = 1. Minimum water temperature was defined as follows: <0 °C = 1; 1–10 °C = 2; >10 °C = 3. Maximum water temperature was set as follows: >40 °C = 1; 26–40 °C = 2; <25 °C = 3. The standard baseline (score 3) for relative humidity was set between 30 and 50%, and all values above or below were translated to 1.

Motion and thermal comfort were considered a priority above energy production potential. However, this priority could be reversed and provide different results according to the stakeholders' objectives and specific needs. The only exception was wind speed, as all values were generally low: values above 3 m/s, enough for micro-eolic systems to work, were assigned a 3. Regarding temperature, maximum values above 41 °C and minimum values below 5 °C were assigned a 1. Wave heights were defined as 0–40 m = 3; 40–60 m = 2; >60 m = 1. The current speed was similar in all regions and was assigned a 1. Salinity levels were set as follows: <37.33 psu = 1; 37.33–38.33 psu = 2; >38.33 psu = 3.

Microclimate and hydrographic parameters were calculated by considering the average between the Civitavecchia and Anzio tide gauges for area 2 and between the Ravenna and Venezia tide gauges for area 4.

After a thorough comparison, area 7 emerged as the optimal site, closely followed by areas 2 and 3. However, according to our comprehensive evaluation, area 4 is the least suitable.

This data-driven approach and the research findings themselves provide valuable insights that could serve as a foundation for targeted policy development, zoning regulations, and financial mechanisms to support the integration of floating city development into urban planning. More specifically, national and local governments could establish zoning regulations that designate suitable water areas for floating urban expansion, while considering environmental protection, maritime traffic, and urban needs. Most importantly, they could define legal ownership frameworks and streamlined permitting procedures for floating districts, addressing jurisdictional challenges, maritime law considerations, and environmental responsibilities to ensure ecological sustainability.

Table 3. Comparative analysis of the different potential sites for FUD according to specific parameters.

Parameters	Area 1		Area 2		Area 3		Area 4		Area 6		Area 7	
	V	S	V	S	V	S	V	S	V	S	V	S
Flood risk class	High	3	High	3	Low	1	Medium	2	High	3	High	3
Urbanization	High density	3	High density	3	Medium density	2	Medium density	2	Medium density	2	High density	3
Proximity to airport [km]	Within 25	2	Within 20	2	Within 100	1	Within 100	1	Within 50	2	Within 5	3
Proximity to seaport [km]	Within 10	2	Within 5	3	Within 5	3	Within 5	3	Within 25	1	Within 5	3
Proximity to train station [km]	Within 5	3	Within 5	3	Within 10	2	Within 5	3	Within 20	1	Within 20	1
Water contamination (above limits)	1	1	2.56	3	1	1	1.22	1	3.1	3	1.22	1
Environmental constraints (Natura 2000)	Yes	1	No	3	No	3	Yes	1	No	3	No	3
Average water fluctuation [m]	0.81	2	0.61	3	0.66	3	0.96	1	1.00	1	0.61	3
Min. water temperature [°C]	10.9	3	12.5	3	12	3	7.05	2	12.2	3	16.1	3
Max. water temperature [°C]	29.1	2	27.2	2	30.6	2	29.5	2	29.4	2	23.1	3
Min. relative humidity [%]	34.6	3	41.2	3	46.1	3	46.6	3	48.8	3	24.5	2
Max. relative humidity [%]	91.1	1	91.3	1	92.6	1	98	1	96.7	1	88.8	1
Wind speed [m/s]	2.8	2	3.2	2	2.6	2	3.9	3	/	/	/	/
Max. air temperature [°C]	29.7	2	30.5	2	31.4	2	29.5	2	31.1	2	37.6	2
Min. air temperature [°C]	4.3	1	5.8	1	7.2	2	2.3	1	5.3	1	7.3	2
Wave height [m]	0.47	2	0.55	2	0.33	3	0.33	3	0.18	3	0.36	3
Current speed [m/s]	0.01	1	0.01	1	0.01	1	0.01	1	0.01	1	0.01	1
Salinity [psu]	38.33	2	38	2	38	2	36.33	1	38	2	38.66	3
Global solar horiz. irradiance [kWh/m^2]	1529	2	1643	2	1600	2	1431	1	1589	2	1769	3
SCORE	**2.0**		**2.32**		**2.05**		**1.79**		**2.00**		**2.39**	

5. Conclusions

This study reveals how coastal–riverine interface zones are generally more susceptible to the cumulative effects of CC and, at the same time, are centers of intense economic, cultural, and social activity. Within these zones, this study identified six zones of interest along the Italian coastline that are vulnerable to SLR and flooding but also hold a high demographic concentration and degree of urbanization: Livorno, Tuscany (area 1); Fiumicino and Rome, Lazio (area 2); Gaeta, Lazio (area 3); Po delta, Emilia-Romagna and Veneto (area 4); Foggia, Puglia (area 6); and Catania, Sicily (area 7). However, further evaluation of these zones revealed additional factors to consider. Environmental constraints like Natura 2000 protected areas apply to the coastal stretch near Livorno, Gaeta, and the Po delta, requiring careful consideration to minimize ecological impacts. Water quality varies quite considerably: areas around the Po delta have considerably high contaminants and, therefore, would require integrated depuration systems. Water level fluctuations vary across the zones, with Venice experiencing the highest. Temperatures are highest in Catania and lowest in Ravenna. Humidity is highest near area 6 and area 4. Regarding energy potential, the Adriatic coast generally has lower wave heights, while the Tyrrhenian coast offers higher solar irradiation. Wind speeds are high near Livorno and Fiumicino.

By assigning weights to different criteria (e.g., minimizing user discomfort vs. maximizing energy production), the most suitable locations can be identified for different development goals. Further research will be needed to address the site-specific technological and logistical challenges associated with FUD construction, accessibility, and integration with existing infrastructure. Public engagement and social acceptance will also be crucial to ensure the social and economic viability of FUD projects. Since this study was limited to an urban and environmental perspective, it was impossible to include an economic analysis concerning the costs and energy prices required to achieve net zero floating development, site-specific buildings, and maintenance costs. In order to estimate specific building, maintenance, and energy costs, it would be necessary to hypothesize a pilot project and reach a certain design detail. In spite of these limitations, future research could also incorporate resident surveys to assess public acceptance and willingness to adopt floating city developments and cost–benefit analyses to evaluate the economic viability, long-term sustainability, and broader socio-environmental impacts of these solutions. Additionally, further studies could examine the potential effects of floating urban development on job creation and tourism, assessing how these projects may stimulate local economies and attract investment. Understanding community perceptions and financial feasibility will provide critical insights for policymakers, urban planners, and investors. By integrating social, economic, and environmental assessments, future studies can refine floating city models, ensuring their scalability, inclusivity, and effectiveness as a climate adaptation strategy and economic driving force.

Overall, this study provides a foundation for the further exploration of FUD as a potential solution for sustainable urban development in Italy, particularly in areas facing CC threats. It highlights the promising potential of nearshore sustainable floating solutions for permanent inhabitation, arguing how floating urban development represents a solution for global land shortages and, if integrated with food and energy systems, a climate-proof sustainable urban expansion opportunity in delta and coastal areas.

All things considered, it is essential to clarify that the urban sprawl of artificial structures in marine environments has widespread ecological and social consequences. While floating developments can be designed to minimize adverse environmental impacts, they will inevitably alter local biodiversity, water quality, and habitat structures. Artificial structures change hydrodynamic patterns, influencing nutrient distribution, sediment transport, and oxygen levels in water, thus the ecological balance and marine biodiversity. Beyond environmental sustainability, the social implications of floating cities are equally critical to their long-term viability. Floating urban developments have the potential to reshape urban life; several challenges related to social equity, affordability, and community integration must be addressed. Higher construction and maintenance costs could make floating cities financially exclusive, leading to the risk of creating luxury enclaves rather than inclusive urban expansions. While floating districts and cities present a promising and innovative approach to sustainable urban expansion in response to climate change, their environmental and social impacts require careful planning and ongoing research. This research represents only a first step in minimizing the impact of floating urban development. The initial priority must be to implement floating settlements only in locations where their environmental impact is limited and the social gain is equal, avoiding sensitive ecosystems and providing an alternative to community displacement. However, site selection alone is not sufficient. The correct and environmentally aware design will play a fundamental role in reducing their footprint and ensuring their integration into marine and social environments. Additionally, continuous environmental monitoring is essential to track their long-term impacts, allowing for adaptive management strategies that mitigate potential ecological disruptions over time. Floating cities can only become a viable and sustainable form of urban development through a combination of responsible site selection, sustainable design principles, and ongoing assessment.

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Interpretation and Comprehensive Evaluation of Regional Water–Land–Energy Coupling System Carrying Capacity

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Abstract: Previous studies on carrying capacity have primarily focused on measuring agricultural production conditions while neglecting the coupling effects among production conditions, production materials, and the external environment (the coupling effects of agricultural water, soil, energy, and the external environment). Therefore, this paper introduces the concept of the carrying capacity of a regional agricultural water–land–energy coupling system (WLECS); develops an evaluation framework comprising 27 indicators from the perspectives of stability, collaboration, and resilience and constructs an improved random forest model based on the red-billed blue magpie optimizer (RBMO). Finally, it is applied to the evaluation of WLECS carrying capacity in China's main grain producing area (Heilongjiang Province). The results demonstrate that the constructed RBMO-RF model exhibits stability and reasonableness with high fitting accuracy. The collaboration weight accounts for the highest proportion (0.438), indicating that the collaboration within the subsystem has the greatest impact on the carrying capacity. In terms of time scale, the WLECS carrying capacity in Heilongjiang Province shows an upward trend, characterized by three stages: a "low-level fluctuation period", a "growth period", and a "rapid growth period". In terms of spatial scale, the overall spatial pattern is low in the West and high in the East, and stable in the North and South. The key driving factors are the effective irrigation index, indirect water footprint, and agricultural water-land matching degree. The research results demonstrate the carrying capacity of the WLE coupling system holds significant implications for formulating regional agricultural resource optimization allocation plans and promoting agricultural sustainable development.

Keywords: carrying capacity; red-billed blue magpie optimizer; random forest; coupling system

1. Introduction

Water, land, and energy are important natural resources for maintaining the operation of social systems. They are also the core of regional agricultural system production [1,2] and the material basis for human survival and livelihood [3]. Rapid social and economic development, accelerated urbanization, continuous population growth, energy depletion, and environmental degradation have created significant challenges. These factors have resulted in issues such as resource crowding out, shortages, and regional structural disruptions of water, land, and energy in agricultural production. Consequently, these problems are likely to intensify the imbalance between industrial structure adjustment and resource supply and demand [4]. Current demand and resource use trajectories are threatening to undermine the inclusiveness and sustainability of development. For example, by 2050, the Food and Agriculture Organization (FAO) projects a 70 per cent increase in food production, and the World Energy Council (WEC) projects a 100 per cent increase in energy supply. These trajectories must be curbed by a more efficient use of resources and reduced wastage, as well as demand management. However, there exists a close and complex coupling relationship among agricultural water, land, and energy [5]. Clarifying the mechanism of the water–land–energy coupling system (WLECS) in agricultural production [6] and conducting research on the agricultural water–land–energy coupling system carrying capacity (WLECSCC) will help promote resource conservation, improve production efficiency, alleviate the imbalance between resource supply and demand, ensure food security, and achieve sustainable regional economy development.

The term "carrying capacity" originally referred to a physical quantity in mechanics, namely the maximum (limit) load that an object can withstand without sustaining damage [7]. It was initially borrowed by disciplines such as demography, applied ecology, and population biology [8–11], all of which utilized the concept of "upper limit of quantity". Subsequently, the FAO and the United Nations Educational, Scientific and Cultural Organization (UNESCO) organized large-scale studies on carrying capacity, and proposed various definitions and quantification methods [12]. This led to a new wave of research on carrying capacity.

Currently, the primary research methods for studying carrying capacity can be categorized into three main approaches: the empirical formula method, the index system evaluation method, and the system analysis method [13,14]. The empirical formula method offers the advantage of relatively simple calculations, but its disadvantage is that it inadequately considers the interrelationships among resources, the environment, the economy, and society. The indicator system evaluation method excels in its deep application of mathematical theories, yet it faces challenges in standardizing indicator selection [15,16]. The system analysis method accounts for the complexity and systematic nature of the resource–economy–society ecology, but it involves complex calculations and faces difficulties in application and promotion [17,18]. In summary, considering the inherent properties of carrying capacity, the index system evaluation method is the mainstream research approach in the current academic community. However, for the carrying capacity of complex agricultural production systems, previous studies have either focused on the relationship between the constraints of single water or land resources and social, economic, and natural systems or integrated water and land resource systems for evaluation. Not only does this ignore the impact of energy systems beyond natural conditions on agricultural production, but it also fails to consider the complex nonlinearity and feedback relationships among the interactions of various subsystems. Additionally, it lacks a comprehensive evaluation of WLECSCC from an integrated management perspective of factor coordination, departmental collaboration, and system control. Against this background, conducting regional agricultural WLECSCC evaluation research is of significant importance for alleviating the imbalance between resource supply and demand under the existing agricultural planting model.

To address the complex WLECSCC evaluation problem, we first need to analyze the intrinsic relationships within a coupled system. Based on this analysis, we should design an indicator system with minimal information overlap among the evaluation indicators, objectively determine the weights of these indicators, and finally use intelligent algorithms to optimize model accuracy, thereby enhancing the rationality of the evaluation results. The entropy weight method for determining indicator weights offers the advantages of objectivity, simplicity in operation, and effective reflection of the indicator differentiation ability, making it widely used in multi-objective evaluation fields [19–21]. With the development of artificial intelligence, machine learning methods have been widely applied in multi-objective evaluations of agricultural areas [22,23]. Machine learning can automatically analyze and extract patterns from multidimensional data, using these patterns to predict unknown data with high accuracy and the ability to handle complex nonlinear problems [23]. An evaluation simulation model is constructed using machine learning, with the evaluation index threshold serving as the input variable and the carrying capacity threshold serving as the output variable. The measured index data are substituted into the constructed model as the input source, and the output source obtained is the required evaluation target [22]. The evaluation results are not only scientifically sound and reasonable but can also efficiently identify key driving factors. However, a disadvantage is that the modeling process is relatively complex, and the selection of modeling methods and model parameters can directly influence the accuracy of the measurement results. The models that are currently used most in the field of multi-objective evaluation are projection pursuit (PP) [24], artificial neural networks (ANNs) [25], support vector machines (SVMs) [26], and extreme learning machines (ELMs) [27]. The accuracy of the PP model is overly dependent on the projection direction and has poor stability. The ANN model's fitting process suffers from issues of overfitting and becoming trapped in local minima. The SVM model's function is excessively complex and inconvenient to operate. The ELM model randomly initializes the weights between the input layer and the hidden layer, and the hidden layer is too high, which adversely affects the generalization performance of the model. The random forest (RF) model offers several advantages, including simple operation, excellent performance, fast convergence speed, minimal parameter tuning requirements, automatic identification of feature importance, high tolerance to data noise, and strong anti-interference and anti-overfitting capabilities [28]. Consequently, it is widely used in multi-objective evaluation. Therefore, this paper selects the random forest model as the evaluation model.

In the traditional random forest model, the number of decision trees N and the number of candidate split attributes m are two key parameters that significantly influence the model's accuracy [29]. Before the N value reaches its optimal point, a larger N generally improves model performance. The m value determines the ability of the decision tree and the correlation between them [29]. Therefore, to enhance the performance of the random forest model, it is essential to determine the optimal values for N and m. The RBMO algorithm has the advantages of automation, global search, fitness evaluation, and performance improvement in model parameter optimization problems, and has been well applied in practice. To address the challenge of optimal parameter selection in the traditional RF model, this paper introduces the red-billed blue magpie optimizer (RBMO) [30]. An improved RF model based on the RBMO algorithm was constructed, utilizing the RBMO algorithm to automatically optimize the N and m parameters, thereby enhancing the accuracy of the RF model.

Based on this, this paper proposes the concept of WLECSCC and constructs the RBMO-RF model using Heilongjiang Province, China's primary grain-producing region, as the research base. This study aims to alleviate the imbalance between the supply and demand for water, land, and energy under the current agricultural planting model and provide guidance for decision-makers in formulating more effective water, land, and energy allocation plans. The primary potential contributions of this study are as follows:

(1) The concept of regional WLECSCC is proposed;
(2) A set of regional WLECSCC evaluation indicators are constructed based on the principles of stability, collaboration, and resilience;
(3) The RBMO-RF model is constructed to analyze the spatiotemporal characteristics of regional WLECSCC;
(4) The driving mechanisms underlying WLECSCC are analyzed using the RBMO-RF model.

2. Study Area Overview and Methods

2.1. Study Area

Heilongjiang Province, located in northeastern China between 121°11′ and 135°05′ east longitude and 43°26′ and 53°33′ north latitude, encompasses 12 prefecture-level cities, including Harbin, Qiqihar, and Mudanjiang, and the Greater Khingan Range Region (Figure 1). It has a total area of 473,000 km^2 and serves as a major agricultural province and energy-producing province, as well as an important industrial base in China. It has a temperate continental monsoon climate, with four major water systems—the Heilongjiang River, Songhua River, Wusuli River, and Suifen River—as well as two major black soil regions: the Sanjiang Plain and the Songnen Plain. Due to its unique land properties and hydrological and climatic conditions, Heilongjiang Province has become China's largest commercial grain production base, ranking first in the country in grain output. It serves as the "ballast stone" of China's food security. Due to the excessive pursuit of short-term economic benefits in recent years and the long-term focus on reclamation, while neglecting management, a series of resource and environmental issues have emerged. These include an imbalance in the agricultural water use structure, deterioration of water environment quality, decline in arable land fertility, and low agricultural energy utilization efficiency. The current agricultural development model has strayed from the sustainable development trajectory of "green agriculture". Against this background, clarifying the characteristics of the WLECS in Heilongjiang Province and conducting research on the WLECSCC will help to coordinate the relationship between agricultural water, land, and energy resources and formulate a more effective allocation plan for these resources, as well as promoting the sustainable use of regional agricultural resources and the green development of agricultural economy. In addition, Heilongjiang Province is located in one of the world's three major black soil conservation areas. Conducting research on the WLECSCC in this region plays an essential role in ensuring global food security, sustaining the fertility of black soil farmland, and facilitating the dissemination of agricultural technology.

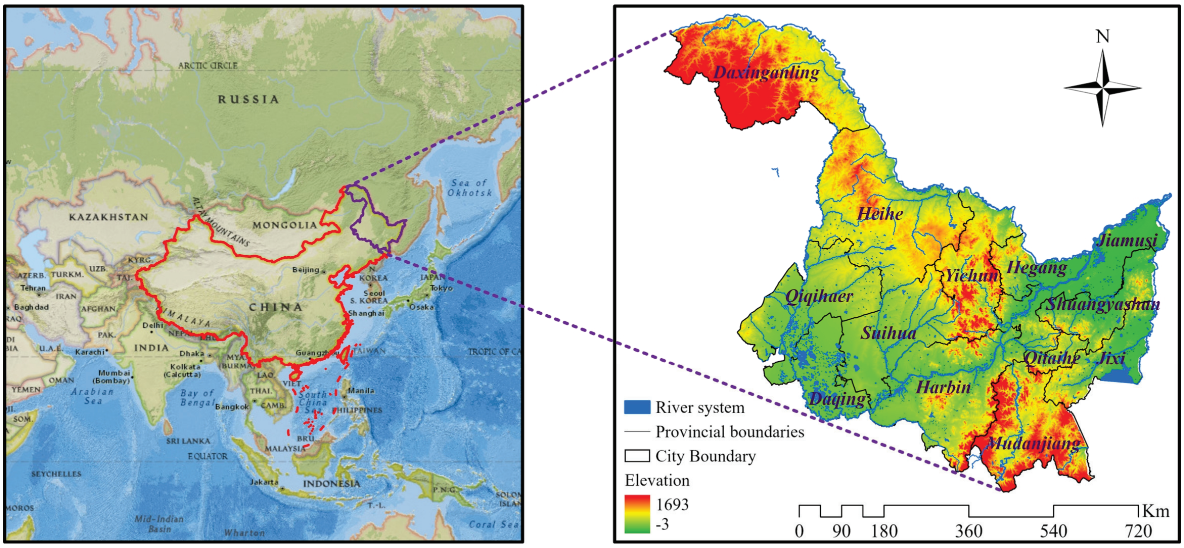

Figure 1. Geographical divisions of Heilongjiang Province.

2.2. Date Source

Data were collected from the "Heilongjiang Statistical Yearbook" (2004–2022), published by the Heilongjiang Provincial Bureau of Statistics, China. Additionally, data from the "Heilongjiang Provincial Water Resources Bulletin" (2004–2022) and the "Heilongjiang Provincial Water Resources Comprehensive Annual Report" (2004–2022) were obtained from the Heilongjiang Provincial Water Resources Department. After sorting and calculating, we obtained data on water resources, land resources, energy, and other indicators for 19 years across 13 cities and districts in Heilongjiang Province, China. Relevant economic indicators were deflated and utilized for the analysis of WLECSCC-related issues.

2.3. Methodology

2.3.1. Analysis of the Connotation of WLECSCC

Agricultural production depends on natural conditions and the input of agricultural production materials. The agricultural system can only operate cyclically by relying on water, land, and energy inputs. Water is an essential substance and medium for crop growth and photosynthesis; land provides a place and nutrient source for crops; and energy serves as the power source for the operation of the agricultural system. The three major elements of agriculture, water, land, and energy, cover the raw materials, sites, and power of regional agricultural production [31], and form the core components of the regional agricultural economic system through water cycles, land use, and energy consumption. There are complex influences or conversion relationships in this system, including "water–land", "water–energy", and "land–energy" [1]. Regarding "water–land", the construction of agricultural irrigation and drainage projects and the application and development of water-saving technologies and water-saving policies will change the land-use type. At the same time, non-point source pollution generated by agricultural planting will affect land quality and thus affect the land use structure. As for "water–energy", agricultural water extraction, water supply, water use, and drainage consume a lot of energy. At the same time, the production or extraction process of agricultural energy, such as seeds, fertilizers, pesticides, and diesel, requires a lot of water resources. As for "land–energy", agricultural land use and land fertility maintenance require large amounts of energy, and agricultural energy extraction and the construction of its supporting facilities require land investment. Changes in land-use types caused by social development will affect water distribution and circulation. Hydropower will generate new energy, and some agricultural and sideline products will be converted into biomass energy to change the energy utilization structure. The interactions between these factors comprise complex nonlinear and feedback relationships [31], thus forming a regional agricultural water–land–energy coupling system (WLECS).

A WLECS not only involves the interconnection and interaction of the three major systems within it, namely the water system, land system, and energy system, but is also closely related to the external social–economic–environmental system, together forming the main body of the regional agricultural economic system. Among these, the WLECS is the core of agricultural production, supporting agriculture as an important foundation for human economic and social development. The social–economic–environmental system provides external driving forces for the WLECS, while the WLECS can also exert coercive effects on it. Therefore, it is particularly important to clarify the system coupling mechanism and understand the functions and influencing factors of each subsystem. In this process, water, land, and energy are the main bodies of the WLECS and the basic production and exchange units of materials and energy, while the carrying capacity determines the upper limit of the balanced development of the WLECS. Therefore, conducting research on WLECSCC evaluation is of great significance for optimizing regional water, land, and energy allocation, coordinating the relationship among the three and promoting the sustainable development of the regional economy.

Referring to the previous research results [4,7,13,14,32,33], WLECSCC is defined here as follows: "At a certain historical development stage, based on the foreseeable technological, economic and social development levels, with sustainable development as the principle and with the maintenance of healthy ecological environment development as the condition, the maximum capacity of regional population growth and economic development under the premise that regional agricultural water, land and energy resources are rationally developed and utilized". Taking into account the complex nonlinear and feedback relationship between the WLECS and the external environment, WLECSCC is decomposed into "stability", "collaboration", and "resilience", among which "stability" is characterized by the resource endowment and efficient utilization carrying capacity of each subsystem of water resources, land resources, and energy resources; "collaboration" is characterized by the carrying capacity of dependency transformation and interaction of each subsystem; and "resilience" is characterized by the carrying capacity of each subsystem to resist the external environment and absorb the driving force of the external environment. The connotations of the WLECSCC are shown in Figure 2.

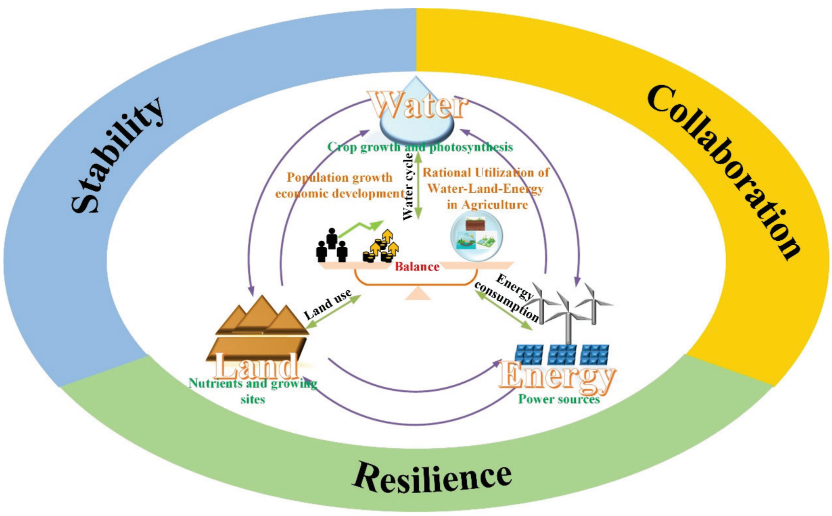

Figure 2. WLECSCC connotation framework.

2.3.2. Construction of Evaluation Index System

Scientifically constructing an indicator system is the key to evaluating WLECSCC. Traditional indicator screening methods mainly include theoretical analysis and expert consultation. The idea of constructing the indicators in this article was based on using theoretical analytical thinking. The specific steps in this process are as follows: consult a large amount of research, grasp the research direction, build a research framework, explain the research connotations, and select evaluation indicators. References [31–36] selected typical and representative evaluation indicators. On this basis, based on the principles of scientificity, necessity, operability, pertinence, and policy relevance, and based on the connotation analysis of WLECSCC and the characteristics of Heilongjiang Province, 27 indicators that can reflect the WLECSCC of Heilongjiang Province were selected with "stability", "collaboration", and "resilience" as the criteria. The evaluation index system is shown in Figure 3.

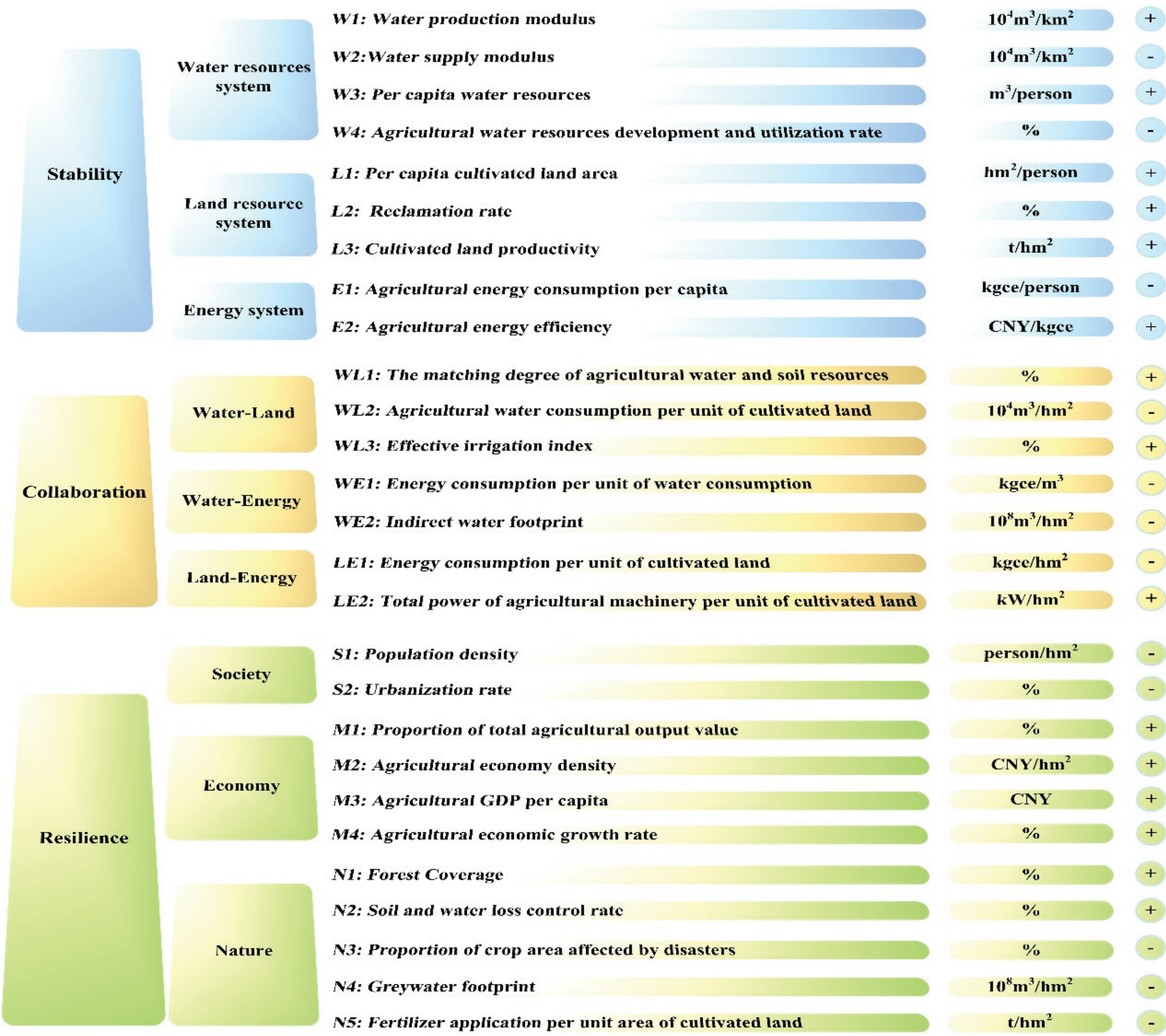

Figure 3. WLECSCC evaluation index system. Note: In this figure, "+" indicates a positive indicator and "−" indicates a negative indicator. The simplified naming of indicators adopts the method of listing subsystems in alphabetical order. In order to distinguish energy from economic indicators, economic indicators are represented by "M".

2.3.3. Normalization of Indicators

After normalization, the indicators can accelerate algorithm convergence, improve model accuracy and algorithm stability, and eliminate the impact of the different dimensions of evaluation indicators of each system. Compared with other normalization methods, the max–min method is frequently employed in scenarios where the data range is known. It offers the advantages of simplicity, ease of use, and preservation of the proportional relationships between data points. It has been extensively utilized in neural networks and other machine learning models. The process is detailed in the literature [29]. The indicator data in this study were comprehensively detailed, and the final evaluation was conducted using machine learning techniques. Accordingly, this research employed the max–min normalization method to standardize the evaluation indicators.

2.3.4. Determination of Indicator Weights

The entropy weighting method is an objective weighting method. In information theory, entropy is a measure of the degree of disorder in a system, used to determine weights, where the larger the entropy value, the smaller the amount of information provided by the indicator and the smaller the weight of the indicator, and vice versa. In the field of multi-objective evaluation, in order to avoid subjective weighting, the entropy weight method is widely used to determine the weights of evaluation system indicators. The main process of determining the index weight via the entropy weight method is as follows: data standardization, entropy value calculation, weight calculation, and weighted evaluation. The process will not be described here, and the detailed process can be found in the literature [37].

2.3.5. Random Forest Model

RF is an ensemble learning model based on decision trees [38]. The basic idea is to use multiple independent decision trees to form an ensemble decision tree, and the performance is determined by the number of decision trees N and the splitting attribute m. RF can improve prediction accuracy without significantly increasing the calculation load and is insensitive to multicollinearity. The results are relatively robust to missing data and unbalanced data. Please refer to the literature for the detailed steps of this process [39].

2.3.6. Red-Billed Blue Magpie Optimizer

The red-billed blue magpie optimizer (RBMO) is a new type of swarm intelligence optimization algorithm proposed by Shengwei Fu in 2024. This algorithm is based on the cooperation and competition mechanism of red-billed blue magpies when foraging to find the optimal solution. Compared with traditional algorithms, RBMO has the advantages of fast convergence speed, high accuracy, and strong robustness [30]. The steps are as follows:

Step 1: Randomly generate a set of solutions (called a population), where each solution corresponds to the position of a red-billed blue magpie, and set the parameters of the algorithm, such as population size, maximum number of iterations, etc.

$$\mathrm{X}_{\mathrm{i,\,j}} = (UB - LB) \cdot Rand_1 + LB \tag{1}$$

where X is an individual red-billed blue magpie; UB and LB are the upper and lower intervals of the problem to be solved; and $Rand_1$ is a random number between 0 and 1.

Step 2: Simulate the process of the red-billed blue magpie looking for food and update the position as follows:

$$X^i(t+1) = X^i(t) + \left(\frac{1}{p}\cdot\sum_{m=1}^{p} X^m(t) \ - X^{rs}(t)\right)\cdot Rand_2 \quad (2)$$

$$X^i(t+1) = X^i(t) + \left(\frac{1}{q}\cdot\sum_{m=1}^{q} X^m(t) \ - X^{rs}(t)\right)\cdot Rand_3 \quad (3)$$

where t is the number of iterations; p represents the number of randomly selected red-billed blue magpies; X^m represents the randomly selected red-billed blue magpie individuals; q represents the randomly selected red-billed blue magpie population; and X^{rs} represents the randomly selected search agent.

Step 3: Simulate the process of a red-billed blue magpie attacking its prey and update the position as follows:

$$X^i(t+1) = X^{food}(t) + CF\cdot\left(\frac{1}{p}\cdot\sum_{m=1}^{p} X^m(t) \ - X^i(t)\right)\cdot Rand_{n_1} \quad (4)$$

$$X^i(t+1) = X^{food}(t) + CF\cdot\left(\frac{1}{q}\cdot\sum_{m=1}^{q} X^m(t) \ - X^i(t)\right)\cdot Rand_{n_2} \quad (5)$$

where X^{food} is the food's location; $CF = (1 - (\frac{t}{T}))^{(2\times\frac{t}{T})}$; and $Rand_{n_1}$ and $Rand_{n_2}$ represent random numbers based on the standard normal distribution.

Step 4: Simulate the process of the red-billed blue magpie storing food and update the position as follows:

$$X^i(t+1) = \begin{cases} X^i(t) & \text{if fitness}^i_{old} > \text{fitness}^i_{new} \\ X^i(t+1) & \text{else} \end{cases} \quad (6)$$

where fitness^i_{old} and fitness^i_{new} represent the fitness values of the red-billed blue magpie before and after the update.

2.3.7. RBMO-RF Model Construction

Let *N* and *m* in the RF model be the search objects of the red-billed blue magpie, and the specific process is as follows:

Step 1: Collect relevant evaluation index data and divide them into a training set and test set;

Step 2: Initialize the red-billed blue magpie individuals; that is, *N* and *m* of the random forest model;

Step 3: Set *RMSE* as the objective function;

Step 4: Based on Formulas (2) and (3), the red-billed blue magpie searches for food;

Step 5: Based on Formulas (4) and (5), the red-billed blue magpie attacks its prey;

Step 6: Based on Formula (6), the food storage operation of the red-billed blue magpie is performed;

Step 7: Determine whether the algorithm has reached the termination condition. If so, repeat Step 4–Step 6.

Step 8: Output the optimal individual of the red-billed blue magpie; that is, *N* and m of the random forest model.

The regional WLECSCC evaluation process based on the RBMO-RF model is shown in Figure 4.

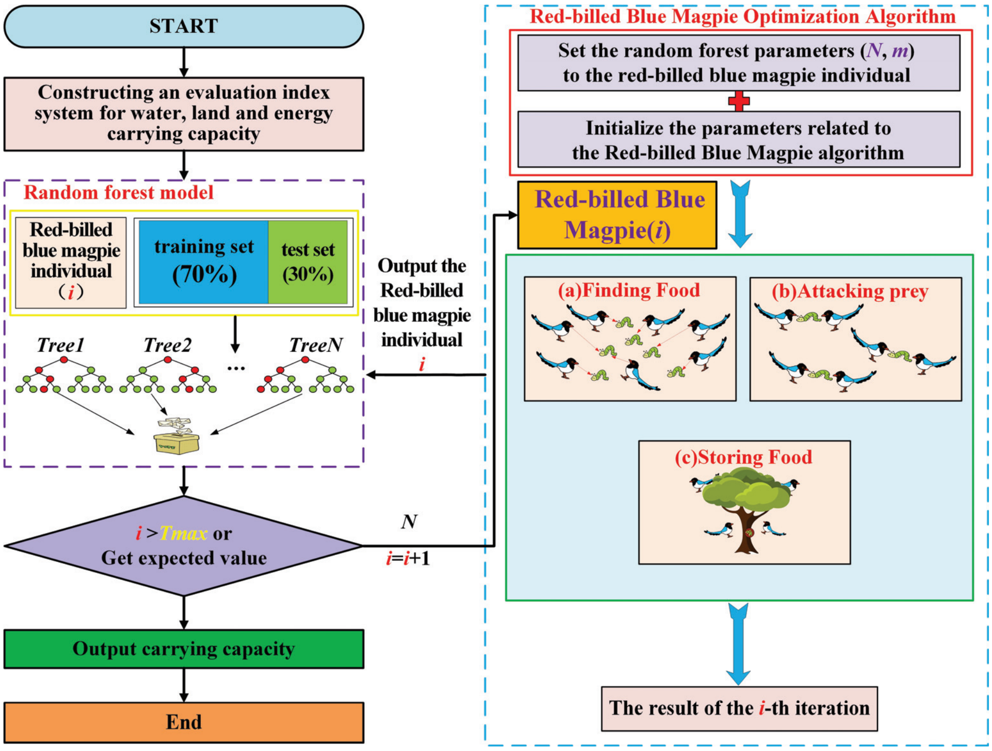

Figure 4. WLECSCC evaluation process based on the RBMO-RF model.

2.3.8. Model Performance Test

Different models were used to evaluate the WLECSCC, and the evaluation results of different models were ranked. The evaluation results were then summed up and re-ranked to obtain the final relatively reasonable ranking. The Spearman rank correlation coefficient of the relatively reasonable ranking of different models was calculated as the rationality coefficient of the evaluation model results [36].

$$R = \frac{1}{\alpha} \cdot \sum_{1}^{\alpha} P_i \tag{7}$$

where R is the model rationality coefficient, α is the number of model runs, and P_i is the Spearman rank coefficient.

Sample entropy can be used to analyze the complexity of time series. The lower the complexity, the higher the stability of the model evaluation results.

$$S = \frac{w}{\sum_{i=1}^{w} SE\left(Result_w\right)} \tag{8}$$

where S is the model stability coefficient, SE is the sample entropy, and $Result_w$ is the αth evaluation result of the model in the wth region.

2.3.9. Mann–Kendall Test

The Mann–Kendall (M-K) is a nonparametric statistical method for analyzing time series data. It can analyze whether the data trend is monotonically rising or falling, does not require the data to follow a specific distribution, and is not affected by outliers [40]. Therefore, this paper used the Mann–Kendall test to evaluate the trend changes in WLECSCC in Heilongjiang Province from 2003 to 2021. When $Z > 0$, it means that the carrying capacity is on an upward trend. When $Z < 0$, it means that the carrying capacity is on a downward trend. When $|Z| > 1.96$, the trend change in the carrying capacity is significant ($p < 0.05$). When the standard normal distribution statistic UF intersects the reverse sequence statistic

UB, the point is considered to be a mutation point [36]. For details on the calculation process of the M-K test, see [41].

3. Results

3.1. Determination of Evaluation Index Level

The determination of the grading standards for evaluation indicators is an important topic of research on WLECSCC evaluation. At present, there is no unified standard for WLECSCC evaluation. With reference to relevant studies [42–44], the natural discontinuity method is adopted and combined with the actual situation in Heilongjiang Province, and the grading standard of WLECSCC evaluation indicators in Heilongjiang Province is determined. The grades are set from I to V. The higher the grade, the greater the WLECSCC. The results are shown in Table 1.

Table 1. Index classification standards.

Indicator	I	II	III	IV	V
W1	<10.87	[10.87, 21.90)	[21.90, 37.90)	[37.90, 47.75)	≥47.75
W2	≥8.59	[5.02, 8.59)	[2.78, 5.02)	[1.04, 2.78)	<1.04
W3	<1491.36	[1491.36, 4465.49)	[4465.49, 9300.34)	[9300.34, 21,563.3)	≥21,563.3
W4	≥1.07	[0.553, 1.07)	[0.293, 0.553)	[0.107, 0.293)	<0.107
L1	<0.222	[0.222, 0.3)	[0.3, 0.406)	[0.406, 0.574)	≥0.574
L2	<0.09	[0.09, 0.362)	[0.362, 0.477)	[0.477, 0.563)	≥0.563
L3	<1.525	[1.525, 2.455)	[2.455, 3.503)	[3.503, 4.786)	≥4.786
E1	≥411.79	[228.55, 411.79)	[140.37, 228.55)	[89.26, 140.37)	<89.26
E2	<48.25	[48.25, 73.96)	[73.96, 107.92)	[107.92, 173.80)	≥173.80
WL1	<0.0598	[0.0598, 0.155)	[0.155, 0.250)	[0.250, 0.421)	≥0.421
WL2	≥0.200	[0.194, 0.200)	[0.144, 0.194)	[0.040, 0.144)	<0.040
WL3	<0.164	[0.164, 0.322)	[0.322, 0.596)	[0.596, 1.126)	≥1.126
WE1	≥21.790	[6.939, 21.790)	[1.664, 6.939)	[0.560, 1.664)	<0.560
WE2	≥4.982	[2.635, 4.982)	[1.435, 2.635)	[0.571, 1.435)	<0.571
LE1	≥1916.21	[1013.46,1916.21)	[599.67, 1013.46)	[344.11, 599.67)	<344.11
LE2	<2.05	[2.05, 3.44)	[3.44, 5.12)	[5.12, 7.31)	≥7.31
S1	≥1.513	[0.955, 1.513)	[0.729, 0.955)	[0.397, 0.729)	<0.397
S2	≥0.731	[0.596, 0.731)	[0.528, 0.596)	[0.388, 0.528)	<0.388
M1	<0.129	[0.129, 0.219)	[0.219, 0.322)	[0.322, 0.500)	≥0.500
M2	<71.81	[71.81, 150.27)	[150.27, 248.95)	[248.95, 425.06)	≥425.06
M3	<4703.02	[4703.02, 8655.16)	[8655.16, 14,115.45)	[14,115.45, 21,275.1)	≥21,275.1
M4	<0.044	[0.044, 0.194)	[0.194, 0.571)	[0.571, 1.116)	≥1.116
N1	<15.43	[15.43, 25.00)	[25.00, 40.20)	[40.20, 65.00)	≥65.00
N2	<0.227	[0.227, 0.369)	[0.369, 0.521)	[0.521, 0.752)	≥0.752
N3	≥0.517	[0.376, 0.517)	[0.242, 0.376)	[0.131, 0.242)	<0.131
N4	≥228.08	[69.09, 228.08)	[39.47, 69.09)	[16.34, 39.47)	<16.34
N5	≥0.150	[0.111, 0.150)	[0.0813, 0.111)	[0.0534, 0.0813)	<0.0534

Note: In the tables, the darker color shading indicates a higher load-carrying grade, which signifies a greater carrying capacity. This principle applies consistently to Tables 2 and 3 as well. In addition, please refer to Figure 3 for the meaning and dimension details of the indicators in the table.

Table 2. *SI*, *CI*, *RI*, and WLECSCC grading evaluation intervals.

Index	I	II	III	IV	V
SI	<1.417	[1.417, 2.759)	[2.759, 3.202)	[3.202, 4.329)	≥4.329
CI	<1.714	[1.714, 2.754)	[2.754,3.147)	[3.147, 4.636)	≥4.636
RI	<1.662	[1.662, 2.809)	[2.809, 3.107)	[3.107, 4.215)	≥4.215
WLECSCC	<1.629	[1.629, 2.774)	[2.774, 3.146)	[3.146,4.425)	≥4.425

Table 3. WLECSCC grades during different stages in various regions of Heilongjiang Province.

Area	Simulation Results			Evaluation Level		
	First Stage	Second Stage	Third Stage	First Stage	Second Stage	Third Stage
Harbin	2.676	2.880	3.075	II	III	III
Qiqihar	2.605	2.635	2.812	II	II	III
Jixi	2.908	3.124	3.253	III	III	IV
Hegang	3.157	3.417	3.698	IV	IV	IV
Shuangyashan	3.001	3.168	3.093	III	IV	III
Daqing	2.753	3.025	3.177	II	III	IV
Yichun	2.962	3.114	3.312	III	III	IV
Jiamusi	2.831	3.101	3.096	III	III	III
Qitaihe	2.812	2.810	2.789	III	III	III
Mudanjiang	2.963	3.089	3.104	III	III	III
Heihe	2.661	2.857	3.005	II	III	III
Suihua	2.582	2.765	3.026	II	II	III
Daxing'anling	2.818	3.153	3.256	III	IV	IV

3.2. Determination of Grade Simulation Interval

The threshold values of each indicator in Table 1 are input into the RBMO-RF model to obtain the grading evaluation intervals of the stability index (*SI*), synergy index (*CI*), resilience index (*RI*), and WLECSCC index. The system level is set to I–V. The higher the level, the greater the system carrying capacity. The results are shown in Table 2.

3.3. Analysis on the Spatiotemporal Variation Characteristics of WLECSCC in the Province

As can be seen from Figure 5a, in terms of the overall trend, the *SI* of Heilongjiang Province showed an upward trend from 2003 to 2021, but with certain volatility. It has two stable periods and two mutation points. The stable periods occurred in 2010–2012 and 2014–2018, respectively. The first mutation point occurred in 2009, which is also the maximum point, with an *SI* of 3.230. The second mutation point occurred in 2013. The lowest value occurred in 2007, with an *SI* of only 2.381. As shown in Figure 5b, the *CI* has an obvious cyclical growth pattern, displayed in 2003–2010, 2011–2012, and 2013–2021. The *CI* is stable in these periods, being 2.636, 2.883, and 3.130, respectively. As can be seen from Figure 5c, the *RI* showed a trend of first increasing and then decreasing in 2003–2006, 2007–2009, and 2010–2013, with a short period of stability in 2013–2014; the *RI* showed a steady growth trend from 2015 to 2021, and the maximum point occurred in 2021 at 3.000.

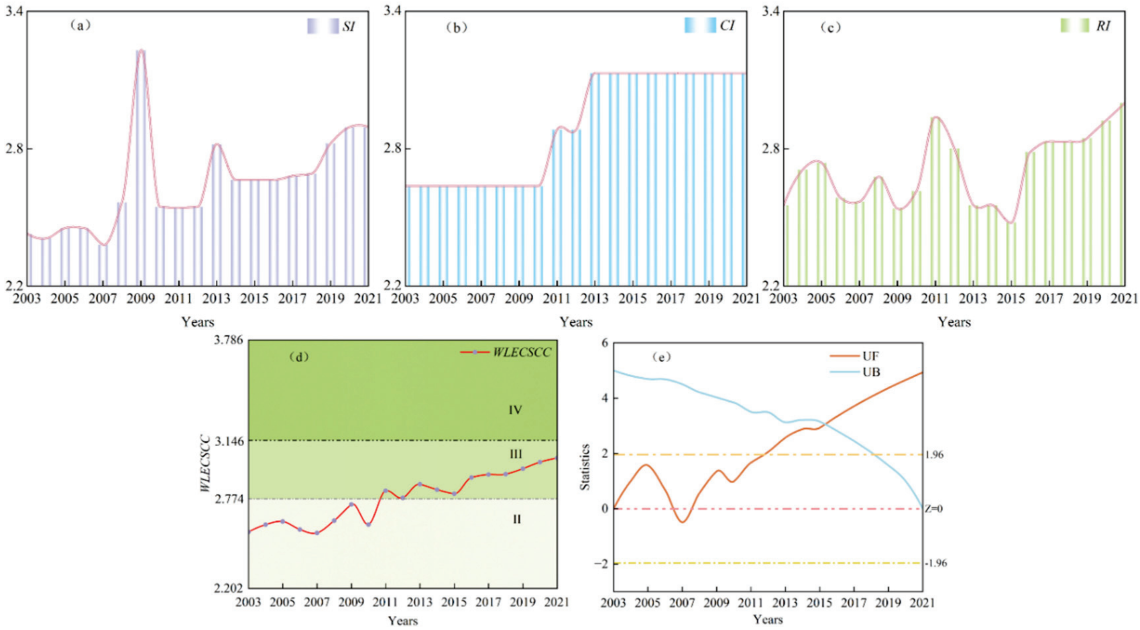

Figure 5. (**a**–**c**) Trend changes in *SI*, *CI*, and *RI* in Heilongjiang Province from 2003 to 2021; (**d**) trend changes in WLECSCC in Heilongjiang Province from 2003 to 2021; (**e**) MK test results of WLECSCC in Heilongjiang Province from 2003 to 2021.

The M-K test was used to analyze the trend of WLECSCC in Heilongjiang Province. The results are shown in Figure 5e. As can be seen from Figure 5d,e, the WLECSCC in Heilongjiang Province showed an upward trend from 2003 to 2021, with certain fluctuations. The UF value from 2003 to 2006 was [0,1.96], indicating that the WLECSCC had an insignificant upward trend. The UF value in 2007 was [−1.96,0], indicating that WLECSCC showed an insignificant downward trend, and the WLECSCC in 2007 was the lowest during the study period, with a value of 2.556. The UF value from 2008 to 2011 was [0,1.96], indicating that WLECSCC had an insignificant upward trend. The UF value of WLECSCC from 2011 to 2021 was greater than 1.96, indicating that WLECSCC showed a significant upward trend at this time. In addition, the two curves UF and UB intersect between 2015 and 2016, indicating that WLECSCC began to mutate at this time, with its upward trend becoming more obvious. It reached its highest level in 2021 at 3.0331. The changing trend of WLECSCC can be divided into three stages. The first stage (2003–2011) is the "low-level fluctuation period", the second stage (2012–2015) is the "growth period", and the third stage (2016–2021) is the "rapid growth period".

3.4. Analysis on the Spatiotemporal Variation Characteristics of the WLECSCC in Cities

3.4.1. Analysis on Interannual Variation Characteristics of the WLECSCC in Cities

Taking all prefecture-level cities in Heilongjiang Province as the research objects, the changes in WLECSCC are divided into three stages: the first stage (2003–2011), the second stage (2012–2015), and the third stage (2016–2021). The indicator data of the three stages were substituted into the RBMO-RF model to obtain the carrying capacity simulation results and evaluation levels of each region in the three stages. The results are shown in Table 3.

As shown in Table 3, from 2003 to 2011, 2012 to 2015, and 2016 to 2021, the WLECSCC grade changes in Jiamusi, Qitaihe, Mudanjiang, and Hegang showed a "stable" characteristic. Jiamusi, Qitaihe, and Mudanjiang remained at level III, and Hegang remained at level IV. The changes in the WLECSCC levels of Suihua, Qiqihar, Jixi, and Yichun showed a "stable first, then increasing" characteristic. From 2003 to 2015, the carrying capacity levels of Suihua and Qiqihar were stable at level II and rose to level III from 2016 to 2021. From 2003 to 2015, the carrying capacity levels of Jixi and Yichun were stable at level III and rose to level IV from 2016 to 2021. The changes in the WLECSCC levels of Heihe, Harbin, and Daxing'anling showed the characteristics of "increasing first and then stabilizing". The carrying capacity levels of Heihe and Harbin increased from level II to level III from 2012 to 2015 and remained at level III from 2012 to 2021. The carrying capacity level of Daxing'anling increased from level III to level IV from 2012 to 2015 and remained at level IV from 2012 to 2021. Daqing's WLECSCC grade shows a "full-range growth" feature, with the carrying capacity grade rising from level II to level III and then to level IV. The WLECSCC grade of Shuangyashan showed a "fluctuating" characteristic, with the carrying capacity grade rising from level III to level IV and then dropping to level III.

From the analysis of the overall development trend, the WLECSCC distribution in various regions was between level III and IV, accounting for 82.1%, and level II accounted for only 17.9%, indicating that the overall WLECSCC level in Heilongjiang Province is good. By comparing the simulation results of level II WLECSCC in different periods, their values are all distributed in the right half of the level II interval [2.202, 2.774), being very close to the lower limit of level III, 2.774. Among them, 71.4% of level II is upgraded to level III. Further analysis shows that when the level simulation result is greater than 2.635, WLECSCC can jump to level III in the later period, and 2.635 is exactly 95% of the lower limit of level III. Similarly, by comparing the simulation results of level III WLECSCC in different periods, the values are distributed in the right half of the level III interval [2.960, 3.146), accounting for 60.9%. The stability of level III is good. When the level simulation result is greater than 3.114, the WLECSCC can jump to level IV in the later period. A value of 3.114 is 99% of the lower limit threshold of level IV. By comparing the simulation results of level IV WLECSCC in different periods, the minimum value is 3.153 and the maximum value is 3.698, and the values are all distributed in the left half of the level IV interval [3.146, 3.786), which proves that the level IV WLECSCC is not high, and the level IV carrying capacity is relatively vulnerable. In the later stage, it is necessary to further rationally allocate resources and strengthen technical control to maintain the current level. In summary, there is no level V WLECSCC in the various regions in Heilongjiang Province from 2003 to 2021, and the risk of fluctuations in the carrying capacity level still exists, with huge potential for improvement. It is worth further analyzing the key driving mechanisms within the WLECSCC and identifying its key driving factors, which will help decision-makers to formulate better resource allocation plans.

3.4.2. Analysis on Spatial Variation Characteristics of WLECSCC in the City

In order to more intuitively analyze the spatial variation characteristics of WLECSCC, the spatial distribution maps of WLECSCC levels in Heilongjiang Province as a whole and in three time periods were drawn, as shown in Figure 6.

As shown in Figure 6a, the *SI* of Jixi, Daqing, Jiamusi, Harbin, and other cities is at a relatively low level and has weak stability, indicating that the water resource, land resource, and energy resource subsystems in these regions have high levels of resource development and demand, and the issue of resource supply imbalances is more prominent. In contrast, the *SI* levels in Yichun, Heihe, and Daxinganling are better, indicating that the degree of resource development and utilization in these areas is low and the internal carrying risk of resources is low. It can be seen from the trend line that the overall change trend in different periods is relatively consistent.

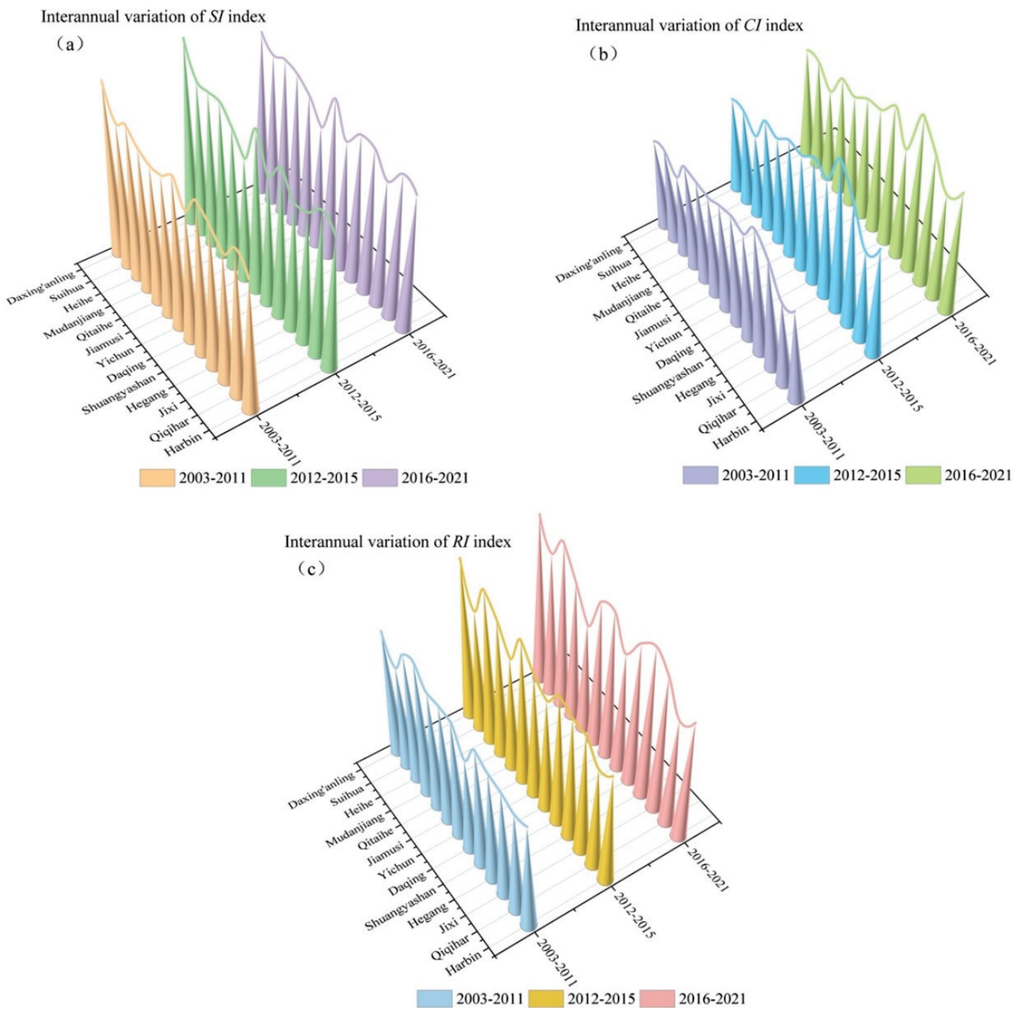

Figure 6. Spatial distribution characteristics of WLECS *SI*, *CI*, and *RI* in various cities in Heilongjiang Province at different times: (**a**) SI; (**b**) CI; (**c**) RI.

As shown in Figure 6b, the *CI* levels of Hegang and Daqing are relatively high, while the *CI* level of Heihe is relatively low, indicating that the resource utilization structure and matching pattern of Hegang and Daqing are more reasonable, while Heihe has problems in resource allocation. Except for Shuangyashan, where the *CI* showed a downward trend from 2016 to 2021, the *CI* of other cities showed an upward trend in different periods, indicating that various cities and districts in Heilongjiang Province are developing healthily in terms of resource allocation.

As can be seen from Figure 6c, compared with the overall development trends of the *CI* and *SI*, the overall change in the *RI* has an obvious fluctuation trend. Among the cities, Qiqihar showed a downward trend in the second stage, the trend for Jiamusi and Mudanjiang declined slightly in the third stage, Qitaihe showed a continuous downward trend, and the rest of the cities showed an upward trend. This shows that Qitaihe lacks the ability to resist natural disasters and external interference, and its social, economic, and environmental systems are facing great challenges and difficulties. It should increase investment in agricultural science and technology and environmental protection to improve this situation.

As can be seen from Figure 7a, from 2003 to 2021, the areas in Heilongjiang Province with low WLECSCC levels were Suihua in the central region and Qiqihar in the western region, and the area with the highest WLECSCC level was Hegang in the northeastern region at level IV. The rest of the areas had a WLECSCC at level III. The overall WLECSCC level showed a spatial pattern of "low in the west, high in the east, and stable in the north and south".

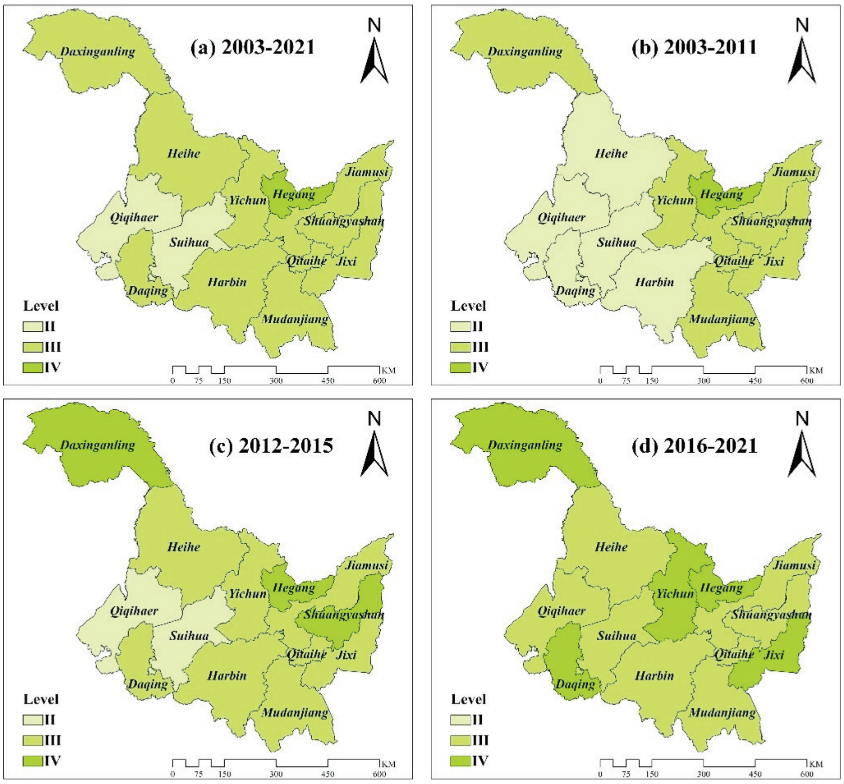

Figure 7. Spatial distribution characteristics of WLECSCC in various cities in Heilongjiang Province during different periods: (**a**) 2003–2021; (**b**) 2003–2011; (**c**) 2012–2015; (**d**) 2016–2021.

As shown in Figure 7b, from 2003 to 2011, the areas in Heilongjiang Province with a low WLECSCC level were located in the western and central regions, with level II accounting for 38.46% and level III accounting for 53.85%. Hegang was the only area with a level IV WLECSCC during this period. The overall WLECSCC level showed a trend of "increasing from west to east".

As shown in Figure 7c, from 2012 to 2015, the overall WLECSCC level showed a trend of "radiating from the middle to all directions". Level II accounted for 15.38% and level III accounted for 61.54%. Compared with 2003–2011, the transition rate for level II reached 60%, Shuangyashan and Daxing'anling jumped from level III to level IV, and Hegang continued to maintain its level IV WLECSCC. The WLECSCC level increased well during this period.

As shown in Figure 7d, the overall WLECSCC level from 2016 to 2021 showed a "fluctuating growth" trend. From northwest to southeast, the spatial pattern was "high-low-high–low–high", and from southwest to northeast, the pattern was "high–low–high", with level III accounting for 61.54% and level IV accounting for 38.46%. Compared with 2012–2015, the carrying capacity during this period increased significantly, with Suihua and Qiqihar rising from level II to level III; Daqing, Yichun, and Jixi jumping from level III to level IV; and Daxing'anling and Hegang continuing to maintain their level IV WLECSCC, while Shuangyashan dropped from level IV to level III.

3.5. Key Driving Factor Analysis

The RBMO-RF model is used to calculate the weights of the criterion layer, the subsystem layer, and each indicator, and the indicator weights are arranged in descending order, with the cumulative weight thresholds set at 25%, 50%, and 75%, respectively. On this basis, the indicator levels are divided into very critical, critical, relatively critical, and generally critical according to the cumulative weights. The results are shown in Figure 8.

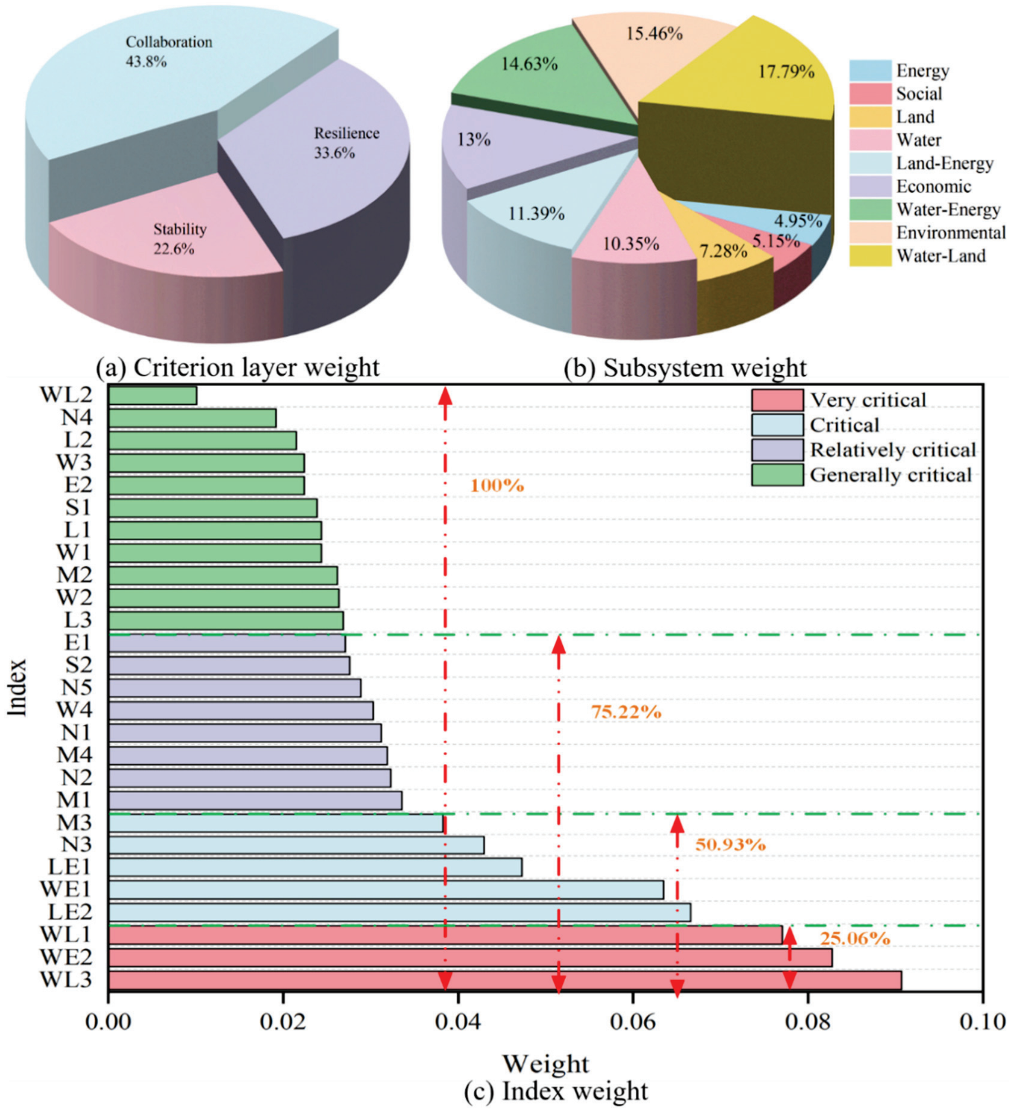

Figure 8. Analysis of importance of different levels: (**a**) Quasi-measurement layer; (**b**) subsystem; (**c**) indicator.

As shown in Figure 8, in terms of the criterion layer weights, the weights of stability, collaboration, and resilience are 0.226, 0.438, and 0.336, respectively, and the weight of collaboration weight is the highest, indicating that the degree of collaboration of each subsystem has the greatest impact on WLECSCC. In terms of subsystem weights, the cumulative weights of the water–land resource system, environmental system, water–energy system, and economic system exceed 60%, indicating that Heilongjiang Province's WLECSCC is not only affected by the coordinated allocation of resource endowments but also by the degree of economic development and environmental protection. This shows that even when resource endowments are not abundant, regional WLECSCC can be improved by optimizing resource allocation plans, improving scientific and technological competitiveness, and paying attention to environmental protection. In terms of indicator weights, the cumulative weights of the first 3, 8, and 16 indicators are 25.06%, 50.93%, and 75.22%, respectively, exceeding the cumulative weight threshold. Therefore, WL3, WE2, and WL1 are set as "very critical indicators", LE2, WE1, LE1, N3, and M3 are set as "critical indicators", M1, N2, M4, N1, W4, N5, S2, and E1 are set as "relatively critical indicators", and the remaining indicators are set as "general critical indicators".

4. Discussion

4.1. Feasibility of WLECSCC Research

Water resources, land resources, and energy resources are the basic resources for human life. The connection, dependence, and constraint relationships between them will inevitably affect the regional industrial structure and resource supply and demand adjustments and further affect economic development and regional stability. Regional agricultural production cannot be separated from the coordinated configuration among the three. Clarifying the coupling relationship among the three is a prerequisite for optimizing the configuration plan and maintaining green agricultural development. The WLECSCC concept and evaluation method proposed in this paper are important links in optimizing the allocation of regional water, land, and energy resources. In 2011, the Bonn Conference in Germany first proposed that there is a complex feedback relationship between water security, food security, and energy security, which triggered a wave of research on the interdependence and trade-offs between these three resources in the nexus relationship and laid the foundation for the study of the mechanism of multi-factor coupling systems [45]. The literature focuses on the study of the regional "water–soil–energy–carbon" coupling mechanism, providing a new theoretical perspective for revealing the coupling relationship between multiple resources and their environmental effects [3]. The literature measures the safety assessment and joint risk probability of the "water–soil–energy" system and clarifies the interactive relationships within the water–soil–energy coupling system [1]. In addition, the theoretical research on carrying capacity in a mature field has been transformed from utilizing a single-factor to a multi-factor integrated perspective. The traditional single-factor research on water, land, and energy carrying capacity obviously does not meet the actual needs of real-life systems. The resource and environmental carrying capacity is closely related to the level of regional social and economic development and human interference. Scholars have conducted many theoretical and empirical studies on the carrying capacity of individual resource subsystems and local related resource systems. The existing research results on the relationship between resource and environmental carrying capacity and social development are rich and solid.

However, this article did not fully consider factors such as climate change, government policies, and global economic trends when designing the indicator system. This shows that the properties of WLECSCC are complex and require more thinking and research in the future. Meteorological conditions such as precipitation and temperature are closely related to the basin hydrological cycle, and through the hydrological cycle process, they further affect the total amount of available water resources and water environment capacity in the basin. Government policy changes have far-reaching impacts on water management, land use planning and energy extraction, which in turn will change the existing agricultural system. Global international trade and competition will also intensify competition for agricultural products and lead agricultural production towards a development model of efficient resource utilization.

In summary, the important foundation laid by many scholars in the field of multi-objective evaluation from the perspective of multi-factor, multi-system, and multi-scale integration provides theoretical support and guidance for the proposal of the WLECSCC concept and evaluation method in this paper.

4.2. Model Comparison

4.2.1. Model Accuracy

To evaluate the performance of the RBMO-RF model, we assessed the RBMO-RF model, the PSO-RF model, and the random forest model using different parameters, namely N = 500, m = 1, $\sqrt{M}$, $(\log_2(M) + 1)$. The mean square error (MSE), mean absolute error (MAE), mean absolute percentage error ($MAPE$), and determination coefficient (R^2) were used as model performance evaluation indicators. Each model was run 50 times, and the average values of the performance evaluation indicators of the above models were calculated. The results are shown in Figure 9.

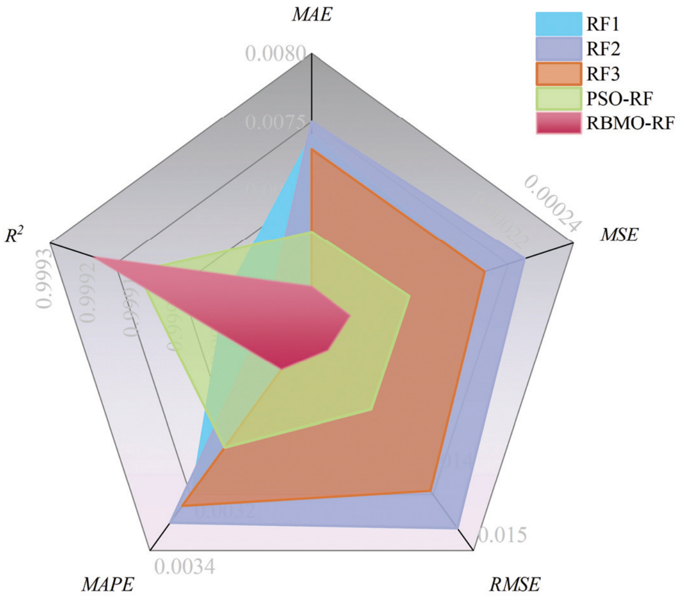

Figure 9. Model performance comparison.

As shown in Figure 9, compared with the PSO-RF, RF1, RF2, and RF3 models, the RBMO-RF model has different degrees of optimization in its MAE, MSE, $RMSE$, $MAPE$, and R^2 values. Its MAE decreased by 5.27%, 13.91%, 16.11%, and 13.73%; its MSE decreased by 13.86%, 19.91%, 13.99%, and 13.99%; its $RMSE$ decreased by 6.28%, 13.24%, 16.28%, and 13.23%; its $MAPE$ decreased by 9.34%, 13.89%, 15.99%, and 15.22%; and its R^2 increased by 0.01%, 0.03%, 0.04%, and 0.05%, respectively. In summary, the RBMO-RF model is a more accurate evaluation method.

4.2.2. Comparison of Evaluation Results of Different Models

The RBMO-RF, PSO-RF, RF1, RF2, and RF3 models were used to evaluate the WLEC-SCC in Heilongjiang Province and various cities. All models were run 50 times. On this basis, the rationality coefficient and stability coefficient of the five models were calculated using Formulas (7) and (8). The detailed results are shown in Table 4.

Table 4. Rationality coefficient and stability coefficient of each model.

Model	RBMO-RF	PSO-RF	RF1	RF2	RF3
R	0.989	0.956	0.941	0.923	0.950
S	2.148	1.571	1.494	1.139	1.531

It can be seen from Table 4 that compared with the PSO-RF, RF1, RF2, and RF3 models, the rationality coefficient R of the RBMO-RF model increased by 3.45%, 5.10%, 7.15%, and 4.11%, respectively, while the stability coefficient S increased by 36.73%, 43.78%, 88.59%, and 40.30%, respectively. Compared with other models, the WLECSCC evaluation results of the RBMO-RF model have obvious advantages in stability and rationality.

4.3. Discussion of Evaluation Results

4.3.1. Analysis of Evaluation Results of the *SI*, *CI*, and *RI*

As for the provincial *SI*, although there is a certain degree of volatility, it shows an overall upward trend, with the maximum point occurring in 2009. By checking the weight ratios of the subsystems of water resources, land resources, and energy resources and the inter-annual changes in indicators, it was found that the water resource subsystem had the highest weight, with a value of 10.35%. In 2009, the W1 indicator changed significantly, increasing by 114.22% compared with 2008. According to the 2009 Heilongjiang Water Resources Bulletin, the increase in the total amount of water resources in Heilongjiang Province accounted for 83.05%, exceeding the multi-year average of 23.2%. The abundant precipitation greatly supplemented the total amount of water resources in the province, causing the *SI* to reach a maximum value that year. Similarly, by checking the 2007 Heilongjiang Water Resources Bulletin, it was found that Heilongjiang Province experienced a dry year that year, with the total water resources decreasing by 23.608 billion m^3 compared with the previous year, resulting in the *SI* reaching a minimum value that year.

The *CI* reflects the synergy between the water and land, water and energy, and land and energy subsystems. Based on the cyclical growth trend of the inter-provincial *CI*, it can be seen that the synergy between the subsystems in Heilongjiang Province is developing in a benign manner. By comparing the weights of specific indicators and the interannual variation patterns, it was found that the two indicators with the largest fluctuations were WL3 and LE2, both of which promoted the *CI*. Compared with 2003–2010, the average growth rates of the two indicators in 2011–2012 and 2013–2021 were 71.57% and 30.73% and 102.45% and 59.93%, respectively.

In terms of the *RI*, the fluctuations are quite obvious. The *RI* reflects the effects of economic environment and human interference on each subsystem, and the leap-like changes conform to the laws of nature. Analysis of specific indicators revealed that M3 and N3 are the main controlling factors. Due to the unpredictability of the N3 factor, it has an inhibitory effect on the *RI*. However, with economic growth and improvements in human environmental awareness, the increase in agricultural technology and environmental protection investment will slow down the inhibitory effect of the N3 factor, which is also the reason for the overall upward trend of the *RI*.

4.3.2. Analysis of Carrying Capacity Index Evaluation Results

Through the M-K test earlier in this article, it can be seen that the change in carrying capacity shows three stages. The first stage (2003–2011) is the “low-level fluctuation period”, the second stage (2012–2015) is the “growth period”, and the third stage (2016–2021) is the “rapid growth period”. The changes in WLECSCC levels in Jiamusi, Qitaihe, Mudanjiang, and Hegang showed a “stable” characteristic. Jiamusi, Qitaihe, and Mudanjiang remained at level III, and Hegang remained at level IV, while the WLECSCC levels of Suihua and Qiqihar were upgraded from level II to level III from 2016 to 2021. Analyzing the changes in *SI*, *CI*, and *RI* during this period, compared with 2003–2015, the average increase rates were 0.14%, 11.96%, and 24.39% and −1.83%, 15.73%, and 2.70%, respectively. It can be seen that the growth of *CI* and *RI* promoted the improvement of the carrying capacity level, and the negative growth of *SI* and the low increase in *CI* and *RI* resulted in Qiqihar’s comprehensive carrying capacity index being lower than that of Suihua. Similarly, the average increase rates of Jixi and Yichun were −3.78%, 6.96%, and 16.31% and 0.90%, 6.65%, and 18.08%, respectively. The changes in WLECSCC levels in Heihe, Harbin, and Daxinganling showed a "first increase and then stable" characteristic. From 2012 to 2015, the carrying capacity levels of Heihe and Harbin increased from level II to level III. Upon analyzing the changes in *SI*, *CI*, and *RI* during this period, it was found that the average increase in each index was 0.31%, 2.14%, and 17.01% and 1.07%, 14.57%, and 2.23%, respectively. The reason why the WLECSCC remained at level III from 2016 to 2021 was that all indexes showed an upward trend. The same is true for Daxing'anling. Daqing is the only city with full-process growth. The average increase in *CI* and *RI* was 19.35% and 20.96%, and the increase in each segment was 11.17%, 16.49%, 7.37%, and 3.84%, respectively. The growth in the second stage was obvious, which caused the overall carrying capacity to jump to the lower threshold of level IV. The growth in the third stage was general, but the level jumped to level IV, indicating that the level IV carrying capacity was not high and there was a risk of decline, which was consistent with the comprehensive evaluation results of the model.

5. Conclusions

This study takes Heilongjiang Province, China's main grain-producing area, as the research area and constructs a regional WLECSCC evaluation index system. Based on this, the RBMO-RF model was used to analyze the spatiotemporal variation characteristics and driving mechanisms of WLECSCC in the study area from 2003 to 2021. The specific conclusions are as follows:

The *SI*, *CI*, and *RI* all show an upward trend. The *SI* is greatly affected by the water resource subsystem. The growth of the *CI* indicates that the synergy among the subsystems in Heilongjiang Province has developed benignly. The change in the *RI* is greatly affected by the environmental subsystem and has a certain degree of uncontrollability.

The weights of stability, collaboration, and resilience are 0.226, 0.438, and 0.336, respectively, indicating that the degree of collaboration of each subsystem has the greatest impact on WLECSCC; through the cumulative weight threshold, WL3, WE2, and WL1 are judged as "very critical indicators", indicating that the level of WLECSCC is not only affected by the coordinated allocation of resource endowments, but the degree of economic development and environmental protection also cannot be ignored.

The M-K test shows that the WLECSCC shows an overall upward trend, but with certain stage changes. The period of 2003–2011 was a period of low-level fluctuations, 2012–2015 was a period of growth, and 2016–2021 was a period of rapid growth.

In terms of model performance, the R and S of the RBMO-RF model are 0.989 and 2.148, respectively, which are higher than those of other models, indicating that its evaluation results are more stable and reasonable.

6. Research Deficiencies and Prospects

6.1. Research Deficiencies

Due to the complexity of the WLE coupled system, the existing research framework does not comprehensively consider climate change, socio-political factors, and global economic trends. It is inevitable that some factors will be overlooked due to the lack of existing knowledge and the impact of technological levels. In addition, the unique dynamic integration properties of carrying capacity require a complete and related dynamic monitoring network of system elements to assist various departments in sharing information.

6.2. Research Prospects

In the future, as production levels and human environmental awareness improve, the level of coordination and cooperation among departments will improve, which will make up for the information omissions caused by insufficient real-time monitoring. In addition, with the continuous development of artificial intelligence, an endless stream of new high-quality intelligent algorithms will emerge, machine learning will become more mature, and the mixed-parameter adjustment of multiple algorithms will further improve the accuracy of model evaluation. Future research will focus on designing a more comprehensive and scientific evaluation indicator system and further exploring the universality of better evaluation models in other regions. Finally, carrying capacity research always serves the purpose of regulation, and future research should focus on formulating carrying capacity regulation plans based on driving mechanisms.

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sustainability

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Article

Building Sustainable Career Skills in Youth Through Adaptive Learning and Competency Self-Assessment Tools †

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Abstract: The DECIDE project entitled "Career choices competencies for the post-pandemic future using multicriteria decision-making", aimed to empower young individuals in their career decision-making by providing them with personalised learning sources and tools to monitor the development of essential career competencies. This paper presents the findings from evaluating two key components of the DECIDE project: an e-guide for developing career competencies and a web-based application that monitors individuals' progress in competency development. These tools help young people identify the skills and knowledge they lack to meet the demands of employers for sustainable and innovative career paths. The e-guide was designed as a self-learning programme that guides users through interactive models focused on building the competencies required for sustainable and innovative career profiles. Pre-tests and post-tests were developed to assess the effectiveness of the e-guide and measure the participants' competency levels before and after engaging with the learning content. The application utilises advanced algorithms and visualisation techniques to analyse pre-test and post-test data, identify competency gaps, and provide users with a clear understanding of their competency development progress and areas for further improvements. The results of the testing and user feedback indicate that the developed tools positively impacted the development of career competencies. The study reveals that the e-guide provided educational value and effectively supported self-directed learning. At the same time, the web-based application offered a valuable tool for self-assessment and identifying competency gaps in career decision-making.

Keywords: career decision-making; career competencies; competencies development; innovative job profiles; personalised adaptive learning; self-assessment; self-learning

1. Introduction

Integrating environmental sustainability concepts into different sectors is crucial in addressing challenges such as climate change, energy efficiency, food insecurity, biodiversity loss, and global pollution. These challenges demand systemic solutions that involve both societal and individual efforts. Integrating these topics into formal and non-formal training education programmes enables individuals to develop the skills and knowledge to cope with complex sustainability challenges. As Elegbede et al. pointed out, such educational involvement encourages individuals to engage in sustainable practices actively. These efforts contribute to the United Nation's Sustainable Development Goals (SDGs), promoting a more resilient and equitable society [1].

Furthermore, integrating sustainability topics into formal education programmes and informal training aligns with education for sustainable development (ESD), which prepares individuals to tackle complex sustainability issues [2]. These issues comprise environmental protection, social equity, economic sustainability, and promoting an environmentally ethical society. These aspects also align with the sustainable learning and education (SLE) concept reported by Hays and Reinders [3]. The SLE concept aims to equip individuals with the skills to thrive in complex contexts and contribute to a better world, aligning with sustainable curricula and learning methods. In addition, the authors of the SLE emphasise systemic thinking and self-sufficiency, suggesting a synergistic approach to promoting sustainability in education and professional development.

Over the last decade, studies and literature reviews revealed a growing interest in integrating sustainability competencies into various study programmes, including teacher education [4,5]. Although many studies focus on assessing sustainability competencies [6] and their integration into pedagogical approaches [7], there is still a lack of a unified framework for integrating and evaluating these competencies at the global and national levels. Self-directed learning courses remain a common pedagogical approach. Studies indicate that students are partially prepared for sustainable learning, especially in digital competencies, which are key to self-directed learning [8]. However, they face difficulties setting goals, managing time, managing stress, and preparing for online lessons.

Our study within the DECIDE project entitled "Career choices competencies for the post-pandemic future using multicriteria decision-making", initially presented at the 19th conference on sustainable development of energy, water, and environment systems (SDEWES) [9], underscores the importance of sustainable development for society's future. We aim to explore how digital tools, such as an optimised web application and an e-guide, develop young people's career competencies. Therefore, our key research question is how these tools support self-directed learning and enable young people to identify and fill gaps in their competencies. In this respect, we include digital strategies and tools to support the development of sustainability competencies in this paper. Our research optimised a previously developed web-based application, whose functionality and testing results are described in detail elsewhere [10,11]. For the DECIDE project, the optimised version of the application allows young people to monitor the development of their career competencies to tackle sustainability challenges in workplaces and society. This study contributes to understanding and addressing sustainability challenges by integrating digital tools with holistic approaches. Tools such as the DECIDE e-guide empower individuals to make informed decisions and foster sustainability-driven decision-making in education and society.

2. Contextual Overview of Sustainability and Digitalisation in Education

2.1. The Importance of Integrating Environmental Sustainability into Educational Programmes

As the environment and society continue to change, understanding the impact of individuals' decisions on society and the economy also evolves. Integrating sustainability into education enhances people's awareness of how their actions affect the environment and society. This focus remains critical for future societal and economic development in the face of current global crises. However, it is essential to acknowledge that the future may not align perfectly with today's sustainability expectations. Achieving sustainable development requires a collective and holistic approach [12] involving education, research, business, policy, and society at local, regional, national, and international levels [13]. Inclusive education must also address the guidelines, laws, rules, and policy frameworks targeting environmental issues. It should encourage active participation, empowering individuals to contribute to collective changes towards environmental responsibility. Education institutions play a pivotal role by implementing actions such as constructing eco-friendly buildings or adopting waste reduction measures [1]. Learning should incorporate sustainability principles to protect natural resources and ensure human well-being, respecting ecological limits. By integrating environmental sustainability into education, individuals are better prepared for a future where sustainability considerations are key. At the same time, they gain competencies to make informed decisions in the face of ongoing sustainability challenges.

The importance of embedding sustainability in higher education (HE) has been recognised by Obrecht et al. Their investigation into study programmes at different levels (Bachelor of Science, Master of Science, and Doctor of Philosophy) found that moderate levels of sustainability are often included in topics such as environmental protection, ecology, and 'green' practices [14]. However, there are significant differences between specific study programmes and fields of study, reflecting students' unequal level of education for future management challenges.

Awareness of sustainable development extends beyond formal education, particularly through citizen science [15,16]. Citizen science fosters collaboration between researchers and volunteers, integrating local knowledge and community values into sustainable policy agendas. Citizen science promotes concepts of environmental sustainability in society and education. In this way, it helps make policies more context-sensitive and responsive to societal and economic needs. Certoma et al. emphasised that urban environments are extremely important for applying crowdsourcing in managing urban sustainable development. They recommend that policymakers allocate more resources to ensure crowdsourcing platforms are open, transparent, interoperable, and scalable [17]. By actively engaging participants in hands-on research and collaborative projects, citizen science contributes to the evolving landscape of education that emphasises digital tools and platforms for fostering environmental consciousness.

2.2. Digitalisation and Tools to Support Sustainable Development in Education

Jackman et al. highlight the need for inclusive digitalisation in education to support sustainable development and the digital economy [18]. Developing digital skills is critical for individuals to thrive in the digital age. Digital education strategies for sustainable development are becoming increasingly important, particularly in light of initiatives such as the United Nations Sustainable Development Goals, especially Goal 4, which emphasises inclusive and quality education for all [19]. ESD recognises the transformative role of digital technology in pedagogy and organisational practices. Leveraging these technologies fosters innovative teaching methods for sustainability education.

One emerging strategy is using massive open online courses (MOOCs) to promote sustainable development education. Gómez Zermeño's research highlights that challenge-based learning in MOOCs strengthens participants' skills that can be applied in real-world scenarios [20]. Future studies should examine how big data can predict digital skills needed to enhance MOOCs' effectiveness in promoting education for sustainable development. Similarly, visualisation tools such as concept maps are valuable for addressing complex sustainability challenges. Concept maps have been increasingly used for educational purposes in recent years, involving technological developments' impact on education's sustainability [21]. Liu et al. found that concept maps clarify hierarchical knowledge structures, aiding content organisation and navigation [22]. Moreover, concept maps can serve as a common knowledge base that promotes collaboration and exchange between students and teachers from different countries or fields of study. It was even shown in [23] that using concept maps in the learning process leads to acquiring new knowledge, skills, and critical thinking. This approach facilitates the transfer of knowledge and skills from educational contexts to real-world applications, underlining the importance of collaborative and personalised learning environments. Embedding environmental sustainability in society and education requires a holistic approach, with room for digital tools and technologies [24]. These technologies can help address challenges holistically and support decision-making on sustainability in education and society.

3. Methods

The research focuses on addressing competencies for career choice in a post-pandemic future using multi-criteria decision-making through adaptive self-directed learning. This study focused on young people aged between 18 and 25. During this period, young people usually make career and further education decisions that can lead to long-term consequences for their lives and employment. This is also the period when young people are coming up against various life milestones, such as finishing secondary school, choosing a higher education study field, having their first interviews with employers and entering the labour market. Young people are exploring their interests, identities, strengths, skills, abilities, and values, which are crucial for making further decisions. These are also the results of different social influences in the real and virtual world. In addition, young people at this time are often confronted with pressures and expectations from society, family, and themselves regarding their success and career, as well as their educational and professional paths. It is, therefore, crucial at this stage to provide supportive tools and opportunities to develop competencies that will enable young people to make more informed decisions and successfully navigate their career paths in sustainable-oriented world scenarios.

Recognising the importance of this crucial period, we stress the need to provide them with accessible tools for self-assessment and competency analysis tailored to their individual needs. Previous studies have shown that young people, for example, in cultures such as South Korea, often face career decision difficulties due to a lack of self-understanding and career self-identity, highlighting the importance of providing tailored career counselling programmes that establish self-concept and identity [25]. This approach aims to empower them to make informed career choices and to open opportunities for them to participate actively in green transition and sustainable development initiatives. By developing and testing the DECIDE e-guide, which contains five self-learning modules and a multi-criteria competency self-assessment tool, and by optimising the online application for monitoring the development of career competencies, we aim to equip young individuals with the tools needed to identify missing competencies that are essential for pursuing sustainable and innovative career paths. Such initiatives not only support young people during a transformative period in their lives, but also provide fundamental data for constructing effective career guidance systems, which could have broader implications for national career development and education policies.

3.1. Testing Location

Training students from different countries and validating the tools developed was conducted in Święta Katarzyna, Poland, over five working days, from 6 to 10 November 2023. The event programme included several activities that encouraged networking, communication, cooperation, teamwork, problem-solving, and acquiring new knowledge and competencies to facilitate young people's future career and educational decisions.

3.2. Target Group

The key target group for the training and tool assessment was young people aged 18–25 who were motivated to participate and learn new skills to develop their career paths and decision-making. The training was also attended by volunteers from different organisations and other project participants motivated to impact developing career decision-making among the youth. The distribution of DECIDE participants by gender and nationality is shown in Figure 1. The project and study involved 11 students or young individuals. However, we did not track data regarding their specific university degree levels or their average age.

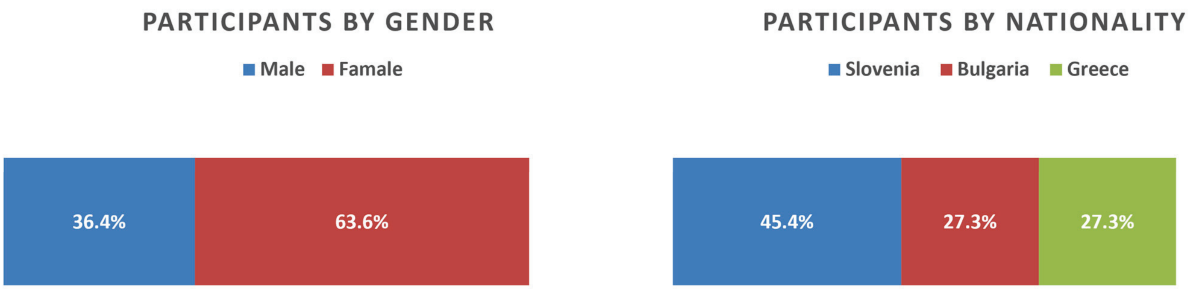

Figure 1. Distribution of DECIDE participants by gender and nationality.

The participant selection process for the training in Poland was carried out in several steps. Each project partner in their respective country contacted various non-governmental organisations working with youth and secondary schools and universities to identify potential candidates willing to participate. Partners conducted inquiries within these organisations to find suitable candidates based on motivation, interest in skill development, ability to collaborate in an international setting, and willingness to travel. The project covered travel and accommodation costs for all selected participants. After the selection, participants received confirmation of their participation.

3.3. Developing E-Guide Modules and Tools for Self-Assessment of Competencies

One of the project activities includes the development of an e-guide with presentations of future job profiles based on the current post-pandemic and labour market requirements about European Union (EU) legal frameworks such as the EU Green Deal (e.g., green jobs, interdisciplinarity and digital literacy…). The document aims to promote a better understanding of long-term career choices among young people. In addition, at the end of the DECIDE e-guide, there is a tool for self-assessment of multi-criteria competencies for young people's career choices through an adaptive learning approach with personalised results for each user based on their competencies input and interests. The methodology for their development follows a user-centred and iterative approach, combining instructional design principles, adaptive learning techniques, and best practices in e-learning development. First, needs are assessed based on previous research, and then content is created that aligns with EU legal frameworks and the post-pandemic labour market. The e-guide is structured around clear learning objectives, theory segments, and interactive activities such as quizzes and exercises designed to engage users and reinforce learning.

The content of the e-guide is also integrated with the DECIDE web application for competencies development monitoring. The e-guide is available online at https://decide-project.eu/ (accessed on 10 December 2024) under the App Table. In Table 1, rows correspond to the titles of five modules, followed by competencies developed during the training in each module and the method of assessing the competency development.

Table 1. Competencies developed by participants in the training modules were assessed using different methods.

Self-Learning Module Title	Competency	Assessing Method
Post-pandemic and green transition of Europe: tackling youth unemployment	Post-pandemic green transition awareness	Pre-test and post-test
Future labour market demands: competencies for new job profiles	Career readiness and competency identification	Pre-test and post-test
The potential of circular and green entrepreneurship	Circular and green entrepreneurship awareness	Pre-test and post-test
Inspirative best practices to follow	Learning to learn	Pre-test and post-test
Self-evaluating multi-criteria tool guidelines	Adapting learning	Self-assessment tool

3.4. Online App Development

The DECIDE project is developing a web application that will allow young people to follow the development of their career competencies while learning online through the DECIDE e-guide. The application is based on the result-oriented engagement system for performance optimisation (RESPO) application developed in the RESPO X project [10], entitled "Revolution of E-Skills with Participatory Online eXpert system". For the DECIDE project, the RESPO application was optimised in terms of database development and functionality, which was significantly simplified. The app allows user registration, where the individual can see the charts for competency development during the training by module.

When pre-test and post-test scores are available, there are several possible approaches to show knowledge and competency development progress in the web application. One option is to show it with a graphical representation of progress with a timeline. The x-axis should show time (pre-test, post-test), and the y-axis should show the number of points achieved. For example, a separate bar graph shows the results before and after the training, giving a clear overview of the changes in knowledge. It is important to use dynamic graphics where the pre-test results are shown in one colour and the post-test results in another. This allows a clear distinction between results before and after training. The graphs should also include trend lines showing the change in the group's average scores before and after the test.

3.5. Testing Procedure

As part of the training, we tested the content of an e-guide for young people on developing career competencies needed for future jobs and the labour market. For the youth training in Kielce, we used an existing online solution, the Socrative platform, to assess the competencies acquired during self-learning with the e-guide. We found the selected online tool to have several advantages when used for self-learning. The digital tool is always free for students to use. Students can install and use it on digital platforms (e.g., smartphones, tablets, laptops, and computers). For lecturers, it allows automatic real-time scores and instant feedback from participants. In this online tool, we prepared a pre-test and post-test for each e-guide module to check the participants' knowledge before and after the lecture for each module except for Module 5. Before the content of each module was discussed during the training, each participant completed an online pre-test with questions on the module topics. The questions were of two types: multiple choice and "fill in the blank space" questions. They then listened to a short lecture and were engaged in interactive exercises. At the end of each training session, students completed a post-test with the same questions as those asked in the pre-test. The respective project partner responsible for developing each module prepared the test questions. Each module included ten multiple-choice questions with one correct answer, where participants had to select the correct answer from four options. Some modules (Modules 2 and 3) also included short answers, requiring participants to fill in 10 missing words or phrases. All questions are publicly available on the project website as part of the e-guide.

The online tests were accessed by scanning a quick response (QR) code that opened a learning room on the Socrative platform. The room with questions was only active during the completion of each test and allowed the lecturer to monitor the students' results in real time. Based on the answers entered, the application calculated the scores. The scores were converted into the levels of career competencies expressed by percent before and after learning the content of the individual modules and transferred into the DECIDE app database. The percentage scores were used to visualise the progress of competency development for each participant and the group.

3.6. Question Types in Pre-Tests and Post-Tests

When developing and testing a web application that measures progress in the development of knowledge and competencies, it is very important to measure knowledge before and after training or self-directed learning. It is desirable that the method of knowledge assessment is as objective and automated as possible and easy to implement [26]. The following types of questions are often used for automatic assessment of answers, where subjective evaluation is avoided:

- Short-answer questions (SAQ), where participants write a brief answer in the text box. The system then compares their answers with predefined keywords or phrases.
- True/false questions, where participants select whether the statement is true or false. The system can automatically check whether they have chosen the correct answer.
- Multiple-choice questions (MCQ), where participants are offered a choice to select the correct answer. The system then checks the option chosen.
- Word matching questions, where participants link pairs of words or expressions; for example, link a definition to the correct expression. The system checks that the pairs are correctly connected.
- Numerical questions, where participants enter a numerical answer and if the answer is within a specific range, the system marks it as correct.
- Fill in the blank space, where participants fill in the missing parts of the sentence with the appropriate word or expression. The system checks to ensure the options are matched. This type is very similar to short-answer questions.
- Correct order, where participants sort the items or answers into the proper order. The system checks that the order is correct.

Two types of questions (multiple-choice questions and fill in the blank space) illustrated in Figure 2 were selected for the DECIDE assessing approach to evaluate knowledge, contributing to an efficient self-evaluation without needing a subjective assessment. Additionally, other studies found that using pre-tests and post-tests as multiple-choice questions can improve teaching and learning performance in online courses [27]. They also found that students were more confident of the correct answers after the post-tests and were better at identifying the correct answers than in the pre-tests. In addition, such a pre-test helped students structure and focus their learning, making it easier for them to identify areas of uncertainty and gaps in their knowledge. This suggests that using these methods can help improve the delivery of online course content and identify areas for improvement in teaching, content delivery, and the design of test questions.

(a) Why is circular and green entrepreneurship significant in today's world?

1 POINT

A It addresses global challenges.

B It fosters sustainability and promotes innovation.

C It ensures a brighter future for future generations.

D All of the above.

(b) ***Fill-in the blank spaces in the text. Write the missing words and separate them with a comma (example: skills, competencies, work).***
The concept of a 1___________ economy revolves around the idea that materials are never discarded as waste, and the environment is 2___________.

2 POINTS

circular, rejuvenated

Figure 2. Two examples of questions in pre-tests and post-tests are multiple-choice questions (**a**) and fill in the blank space (**b**).

4. Results

4.1. Assessing Competencies with Digital Tools

The Socrative app allows users to view live test results. Lecturers can monitor students' progress and see how they are doing as they answer the quiz. They can track a student's progress as a percentage of how many questions they answered. Results are also saved and can be exported for further analysis. Special buttons allow anonymity of the students and their answers, for example, if you broadcast the results page to the whole group of participants. From Figure 3, it is possible to see how many students answered each question correctly in Module 4.

NAME ▲	SCORE % ↕	1	2	3	4	5	6	7	8	9	10
•••••••	✓ 70%	✓ A	✓ A	× B	× C	✓ A	× B	✓ A	✓ A	✓ A	✓ A
•••••••	✓ 70%	✓ A	✓ A	× B	× B	✓ A	× B	✓ A	✓ A	✓ A	✓ A
•••••••	✓ 80%	✓ A	✓ A	✓ A	× D	✓ A	× D	✓ A	✓ A	✓ A	✓ A
•••••••	✓ 70%	✓ A	✓ A	× D	× D	✓ A	× D	✓ A	✓ A	✓ A	✓ A
•••••••	✓ 90%	✓ A	✓ A	× B	✓ A	✓ A	✓ A	✓ A	✓ A	✓ A	✓ A
•••••••	✓ 60%	✓ A	✓ A	× C	× D	× D	× C	✓ A	✓ A	✓ A	✓ A
•••••••	✓ 30%	✓ A	× C	✓ A	× D	× B	✓ A	× D	× C	× C	× C
•••••••	✓ 70%	✓ A	✓ A	× B	✓ A	✓ A	× D	✓ A	× C	✓ A	✓ A
•••••••	✓ 80%	✓ A	✓ A	× B	✓ A	✓ A	× C	✓ A	✓ A	✓ A	✓ A
•••••••	✓ 80%	✓ A	✓ A	× B	✓ A	✓ A	× C	✓ A	✓ A	✓ A	✓ A
10 Class Total		100%	90%	20%	40%	80%	20%	90%	80%	90%	90%

Figure 3. Visualisation of the real-time pre and post-test results using the Socrative application.

Figure 4 shows the progress in developing career competencies for the participants for all modules. Moreover, on average, the group progressed in competencies development in all modules (indicated by circles for class scoring). The highest progress is observed in Module 3 with the title "Potential of circular & green entrepreneurship", where the initial state in terms of knowledge level was also the lowest. We can see that for Module 3, there is a difference of more than 30% in the average progress in the development of knowledge and competencies for the whole group, and for Module 4, there is a difference of more than 20%. For Module 1 and Module 2, the difference is 12%. Due to the small sample size of 11 participants, statistical analysis of the differences between the pre-test and post-test results was not performed, as the statistical power of such tests would be insufficient to provide meaningful or reliable conclusions. This limitation should be considered when interpreting the results of the study. Despite the lack of statistical significance, the qualitative feedback and observed trends from the participants still provide valuable insights into the tools' effectiveness.

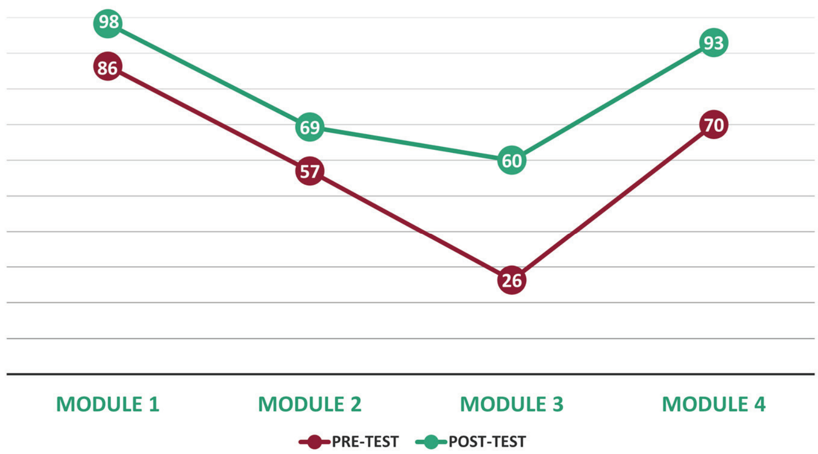

Figure 4. The average score achieved by the whole group of participants in the training, by module, in the pre-tests and post-tests.

The accuracy of assessing students' competencies using pre-test and post-test results can be limited by various factors. Higher scores on a post-test are not necessarily an indicator of students' progress in knowledge and competency development, as these scores may be related to other effects. It is possible that students simply learnt certain information or concepts but not their application in practice. Testing under controlled conditions can result in students learning material for testing purposes only, but not for sustainable use. Additionally, certain students may be more proficient with the tests or have better memory skills, which may affect test results. When assessing students' competencies, it is important to consider several factors and different sources of assessment, such as teachers' evaluations, observations of students during practical activities, mentors' feedback, and students' self-evaluation. More on this topic is explained in Section 5 Discussion.

4.2. Determining Future Job Profiles with a Self-Assessment Tool

The future labour market will likely follow current trends and require job profiles beyond the technical skills that young people acquire in formal education. Employers will demand from young people at the end of their educational career transversal and specific competencies related to critical thinking, systemic decision-making, adaptability, digital skills, advances in materials science and technology development, leadership, and active participation. Young professionals will need to explore and understand dynamic labour markets and continuously learn and upskill to meet the changing demands of employers. In relation to these requirements, we surveyed four European countries (Slovenia, Poland, Greece, and Bulgaria) to identify the five most in-demand occupational profiles in the labour market that the world will need most in the post-pandemic age. The selected areas of employability are key to building a more sustainable society:

- Information technology (IT) enables efficient management of resources, optimisation of processes, and digitisation and automation of systems, contributing to waste reduction, energy efficiency, and improved environmental standards.
- Digital marketing enables businesses to promote sustainable products and services, raise consumer awareness of environmental issues and encourage responsible consumption, which can lead to increased demand for sustainable products and services and stimulate sustainable consumer behaviour.
- Energy and environment are key to the development and implementation of renewable energy, innovative green technologies for remote sensing (e.g., terahertz spectroscopy, light detection and ranging (LIDAR), multispectral and hyperspectral cameras, nuclear magnetic resonance spectroscopy, etc.), and measures to reduce environmental pollution and climate changes.
- Data sciences play an important role in analysing large volumes of data on the environment, climate change, energy efficiency, and sustainable practices, as well as facilitating the interpretation of analyses through various visual and imaging methods.
- Biotechnology enables sustainable food production, the treatment of environmental problems, the improvement of human and animal health, and the development of biodegradable materials.

The most valuable skills and competencies in each job profile, as identified in the project study, are shown in Figure 5. The job profiles are concerned not with one specific job title, but with a professional area of expertise. Thus, Figure 5 summarises several job profiles identified in the project. The figure lists examples of professions for each selected area, such as digital marketing, energy and environment, etc. It highlights the key competencies required for these professions or the competencies that employers expect from candidates seeking employment in these fields.

In Module 5, participants answered a variety of questions about their interests and future career aspirations. Among the 11 participants, almost two-thirds answered in a way that matched their future job profile as a digital marketer. A total of 18% matched the job description for energy and environment specialist and 18% for data scientist. The distribution by future job profiles, based on their interests, educational backgrounds, and career aspirations, is given in Figure 6. The graph displays the results for the students who participated in the training. Two job profiles, i.e., biotechnology expert and IT expert, were not covered at all by the participants' answers. This matching of participants with job profiles may be because the profession of digital marketer is more visible or more popular among young participants. If they are more familiar with the profession, they are more likely to express an interest in it. Participants may also be unfamiliar with the content or requirements of other professions, such as energy and environment specialists or data scientists. Participants may have been more confident in expressing interests and thinking related to communication and marketing (digital marketing) while feeling less confident or less familiar with other areas. Perhaps participants already gained knowledge or experience in their education related to digital marketing, which makes them more inclined towards this area. However, there is a possibility that participants may simply not be interested in certain profiles, such as biotechnology experts and IT experts, because of their personal preferences and goals.

As mentioned by other researchers, self-assessment brings some benefits, but there are doubts about its value and accuracy [28]. Although self-assessment produces consistent results in a variety of situations, the information generated by self-assessment may only partially correspond to the information usually generated by teachers. Nevertheless, self-assessment contributes to higher student achievement and improved student behaviour, as it is an important part of monitoring one's learning processes to make adjustments that deepen learning and improve performance. Although it can also be used as a final assessment method, some research has shown that self-assessment is most useful for self-regulated learning supported by training [29]. Nevertheless, further research on the cognitive and affective mechanisms of self-assessment is important to better understand this process and its usefulness in pedagogical contexts.

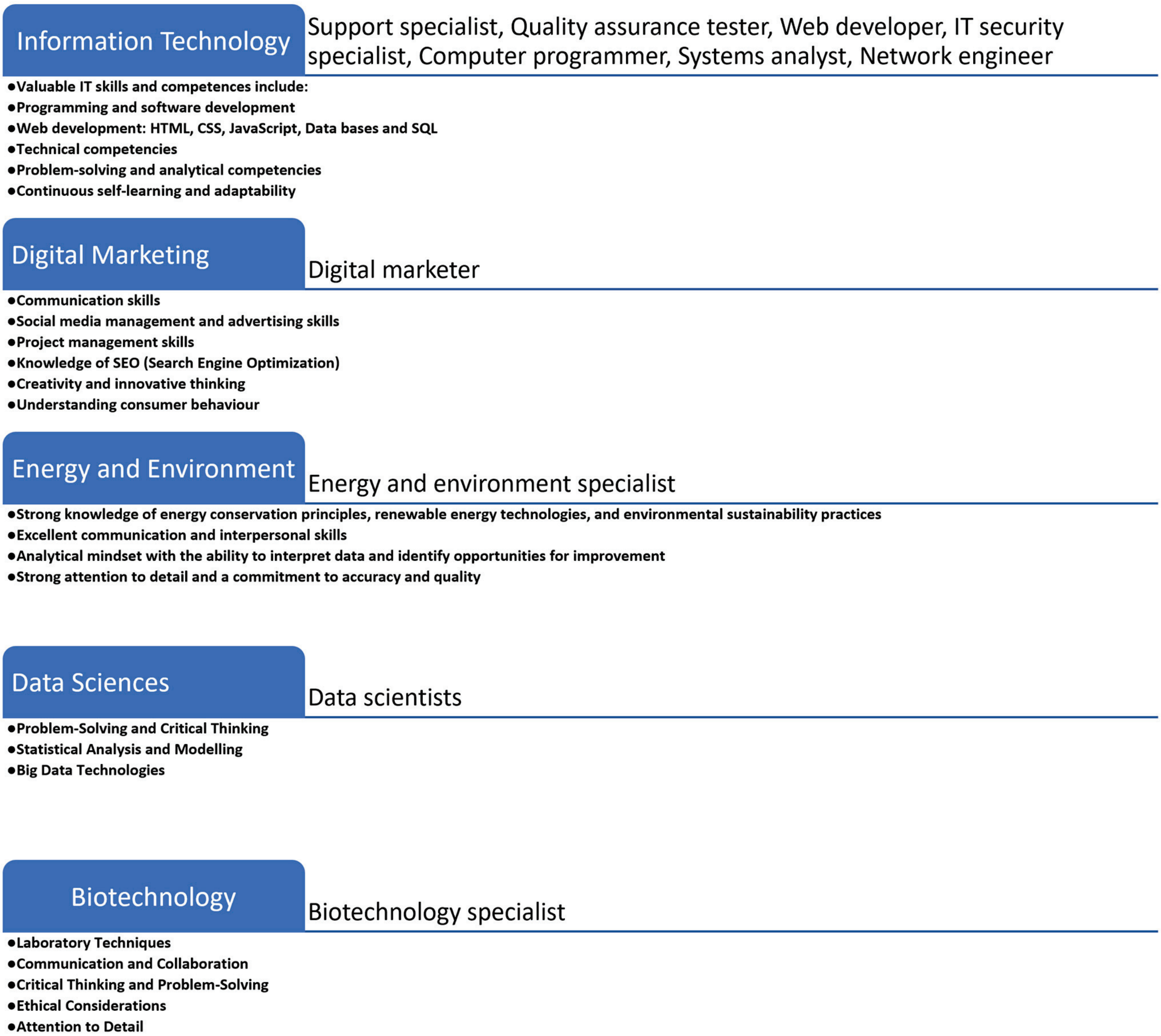

Figure 5. Selected employment fields with job titles and valuable skills.

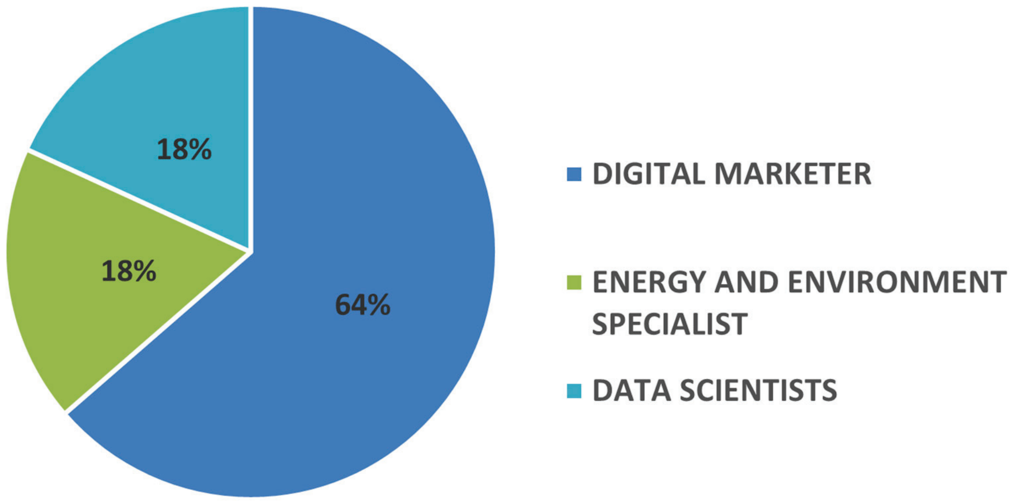

Figure 6. Distribution of participants according to match with future job profiles.

The distribution of results in our research certainly raises the question of the reliability of such self-assessments without deeper psychological profiling of the individual. While some participants may match their future career profiles based on self-assessment, it is important to remember that self-assessment may not capture all the relevant aspects of an individual's personality, interests, skills, and abilities that are crucial in career choice. Without additional psychological profiling, including a deeper analysis of personality traits, values, motivations, goals, and other factors, self-assessment may lead to misinterpretation and unreliable results. In addition, it should be kept in mind that an individual's career choice may also be influenced by external factors such as social norms, environmental influences, job opportunities and personal experiences, which are not necessarily captured in the self-assessment. Therefore, when interpreting the results of questionnaires such as the one in Module 5, caution should be exercised, and potential limitations of self-assessment in the career decision-making process should be considered.

Such self-evaluation questionnaires can serve as a starting point to guide young people through a systematic and critical reflection on their interests, aspirations, values, and educational and career goals. The results obtained from the questionnaires can form the background for exploring different academic and career options for the individual to understand their career preferences in discussions and consultations with mentors or career counsellors. Higher education institutions can use the results of such questionnaires to design and adapt educational programmes that better match the needs and interests of individuals or to offer additional non-formal training that develops in individuals those competencies that they cannot acquire in formal studies but are required by the future labour market. However, when using these results, it is important to be aware of the limitations of such questionnaires and simultaneously use additional methods and tools for career guidance rather than using them as the sole criterion for decision-making.

In using such a self-assessment tool to identify an individual's most optimal future job profiles, it is important to ensure that the questions asked are as objective, clear, and specific as possible. Asking questions that focus on a variety of topics helps to gain a more comprehensive insight into an individual's desires, skills, and personal qualities, allowing for a more accurate assessment of which job profile is most suitable for them. In the further optimisation of the self-assessment tool, the project will try to complement the questions by covering different areas such as skills and interests, work preferences, experience and knowledge, personal qualities, goals and motivation, working environment and conditions, global mindset, work–life balance, complexity of tasks, etc. We will also complement the instructions by indicating whether only one or more answers are possible for each question.

5. Discussion

5.1. Empowering Youth Through Self-Directed Learning and Digital Tools

Self-directed learning (SDL) with digital tools is becoming increasingly popular among young people, especially in the context of not in education, employment, or training (NEET) youth. The article by Kõiv and Saks underscores the necessity for SDL competencies as essential for lifelong learning and personal development, especially for youth disconnected from traditional educational or employment pathways [30]. Moreover, the NEET youth are often characterised by being low in motivation and skills and, therefore, require a holistic approach to develop SDL capabilities. NEET youth do not usually participate in education or work-related activities. Thus, SDL for them should be designed to support the development of positive attitudes, self-motivation, and key employability competencies crucial to overcoming their socio-economic challenges.

Based on the results of our study, we can say that the DECIDE project developed an e-guide that helps young people, including NEET, explore different career options by identifying their interests. The content of the DECIDE e-guide enables young people to deepen their knowledge and skills through self-learning, which can help them overcome the challenges of employment in the transition from education to the labour market while building a successful personal and professional career. Kõiv and Saks mentioned that the content of SDLs should be related to the characteristics, unique personalities, and needs of young people [30]. Motivational factors and elements, such as encouraging self-regulation, goal-setting, and problem-solving skills, are essential to help young people overcome the challenges of a rapidly evolving labour market. This finding complements our study's recommendation that the development of competencies should be supported by focusing on academic knowledge and soft skills such as emotional intelligence, resilience, and adaptability. In this way, young people take part of the responsibility for their career development at the start, which is no longer solely dependent on the prior formal knowledge provided by educational institutions. It also helps individuals to carry out a kind of strengths, weaknesses, opportunities, and threats (SWOT) analysis of oneself, i.e., to discover one's strengths, weaknesses, opportunities, and limits to success in life.

Furthermore, self-learning through self-evaluation makes it easier for young people to adapt more quickly to constantly changing jobs that require new skills, especially in the context of rapid technological change. Today, where skills are becoming essential, it is important to foster young people's commitment to lifelong learning. The readiness of individuals to continuously improve their knowledge and skills is a key factor for career progress. During the DECIDE youth training, the participants also obtained an insight into entrepreneurial skills, encouraging young individuals to explore innovative solutions and potentially pursue entrepreneurial ventures. Furthermore, global perspectives and cross-cultural communication in international teams prepare individuals for careers that involve working with diverse teams or in international settings. Participants benefit from personal development through various interactive activities that prompt self-reflection, goal setting, and developing a personal career plan.

5.2. Assessing Career Competencies Development Through Pre-Test and Post-Test Evaluations

By assessing knowledge before and after each e-guide module, the project gained insight into developing career competencies in the individuals who participated in the training. In all four modules, students successfully developed module-specific career competencies. This progress has been more significant for some students, while for others, it remained at the same level as before the training. There is no negative trend suggesting that the content is inappropriate or too complex for the students.

Module 2 and Module 3 also included “fill in the blank space” questions. Students recognised that this type of question is more difficult to answer because they need to know the exact answers. This difficulty is reflected in the results (Figure 4) of the pre-test and post-tests, where, overall, the level of knowledge both before and after the training was lower compared to Module 1 and Module 4, which included only MCQ. The difficulties students encounter with “fill in the blank space” questions compared to multiple-choice questions can be attributed to several factors. For instance, short-answer questions often require the learner to understand the content in-depth.

In contrast, multiple-choice questions may require the learner to identify the correct answer from all the answers given or randomly select the correct answer. Wijk et al. also found that SAQ or “fill in the blank space” questions are more discriminatory than MCQ, which is consistent with the level of difficulty we found in our study [31]. The need for students to generate their answers rather than identify the correct ones may explain why students perform less well on short-answer questions or “fill in the blank space” questions, as they require more profound understanding and recall, which is more difficult. The authors pointed out that MCQs allowing guessing are less reliable in discriminating between students’ proficiency levels. We also found that in multiple-choice tests, learners may randomly select the correct answer, which undermines the depth of the assessment.

Moreover, short-answer questions typically demand critical thinking and the ability to recall information from memory, which can be more challenging than simply recognising the correct answer among given options in multiple-choice questions. One study showed that both short-answer and multiple-choice quizzes can improve retention if the quizzes are followed by feedback [32]. This suggests that both types of questions and timely feedback can still be very effective for long-term retention.

Students must express their answers accurately and demonstrate a higher level of language and communication skills when answering questions requiring a written response. As a result, even a tiny misspelling can lead to a loss of points. Additionally, sometimes, a missing field in the text may also correspond to different words that are correct but were not expected by the person composing the questionnaire when answering the questions. Furthermore, “fill in the blank space” questions are time-consuming, especially if students find it difficult to recall information or express their thoughts concisely. This challenge can negatively affect their overall performance on the assessment and the time taken to complete the quizzes themselves, as was also evident in the implemented test. Participants took at least twice as long to formulate their answers than to select multiple-choice answers.

Moreover, some students may experience test anxiety, which can be heightened when faced with open-ended questions. The fear of not providing a correct or complete answer may impact their performance. Another important factor is the design of short-answer or “fill in the blank space” questions, including the clarity of instructions and the specificity of what is expected, which can influence how well students perform. Unclear questions can confuse the learner when formulating an answer. Finally, students may have been more familiar and comfortable with the format of multiple-choice questions due to its prevalence in standardised testing. Thus, a shift to short-answer questions or “fill in the blank space” questions might require an adjustment in their approach.

The results suggest that including short answers in pre-tests and post-tests may pose challenges for test designers. In any case, such tests need to provide additional explicit instruction on answering “fill in the blank space” questions, providing opportunities for practice, and emphasising critical thinking and knowledge application in all self-learning modules. The choice of the type of questions to be used for the pre-test and post-tests in the self-assessment depends on several factors, such as the learning objectives, the competencies addressed, the type of learning material, the method of knowledge transfer, the learning outcomes (individual seminar, group exercises, practical project, etc.) and the characteristics of the target group involved in the training. Considering that different types of questions have their benefits and limitations, it is most beneficial to include a combination of various kinds of questions in one test to ensure a balanced assessment, stimulate different aspects of learning, and address the different learning styles of the participants. It is also important to provide clear instructions and, where necessary, to add explanations of the correct answers, regardless of the type of question is chosen.

The module content and complexity may influence the observed differences in progress among the modules. For example, the module with the most progress may have contained more relevant content to the participants or may have been presented in a way that allowed for better understanding. It is also possible that the content in that module may have been less complex or more interesting. Additionally, Module 3 started with the lowest initial knowledge level. As participants had more room for improvement in this module, there was a higher percentage of progress compared to modules with higher baseline knowledge.

Furthermore, Module 3 may have addressed topics relevant to the participants' career goals or personal interests, motivating them to invest more effort and time in learning. This increased motivation likely contributed to their higher levels of engagement, which contributed to better learning outcomes. Participants may be more motivated to overcome challenges and actively participate in some modules' learning processes and activities.

Moreover, individual learning styles and preferences may differ among trainees; therefore, learning methods must be adapted accordingly. It is important to note that a learning method used in one module may not be equally effective in another. Additionally, the effectiveness of the lecturer in each module can play an important role in the delivery of knowledge, as a more experienced lecturer can engage learners more effectively in the classroom, communicate the material more effectively, and improve learning outcomes. Another factor that could have influenced the results is the timing and sequencing of modules. Participants may have built upon that knowledge more effectively if one module addressed foundational concepts or skills necessary for success in subsequent modules. Furthermore, ongoing feedback and assessment during the training programme and adjustments made based on feedback from Module 1 and Module 2 could have positively impacted the design and delivery of Module 3, which was presented to the participants as the final one. Finally, the approach to assessing competencies varied between modules (e.g., different question types), which may have also influenced the effectiveness of each module.

5.3. Visualising Competency Development Progress

Two examples of competency development progress visualisation in the developed application are presented in Figure 7. In Figure 7A, the pre-test result is marked with a blue line, and the post-test result is marked with a green line. The line graph has the x-axis representing each student by identification (ID) number, and the y-axis shows the competency score as a percentage from 0 to 100. In Figure 7B, the pre-test result is marked in blue, and the post-test result is in orange for the selected module. The concentric circles in the pie chart indicate competency development values from 0% to 100%. Each slice of the pie chart represents the result for an individual student, indicated by the student's ID number. To enhance clarity, the line graph in Figure 7A allows easy comparison of individual progress before and after the module, visually showing each student's advancement. Meanwhile, the pie chart in Figure 7B offers a holistic view of the cohort's results, helping to identify overall trends in competency development across students.

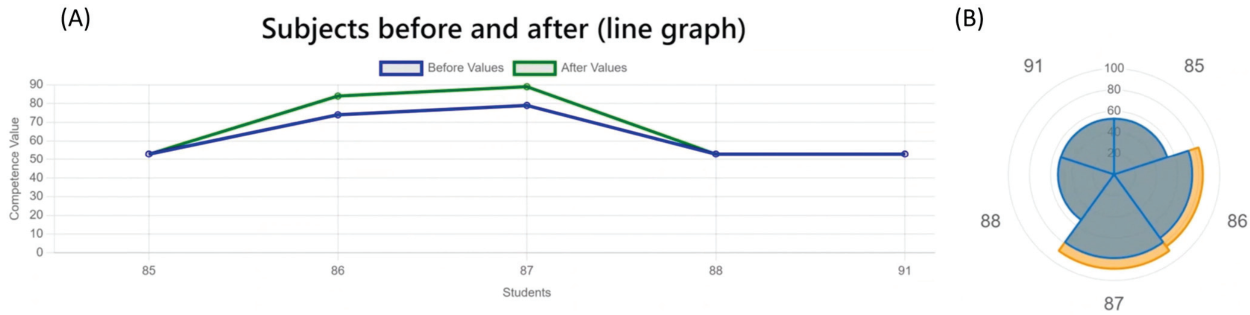

Figure 7. Visualisation of competency development progress in the DECIDE app for different students shown with a line graph (**A**) and a pie chart (**B**).

Other visualisation approaches can be used in the online tool to show, for example, how the results are distributed in different categories before and after testing, such as a pie chart showing the proportions of correct answers in different competencies or learning modules. When visualising results, graphics with icons or symbols representing progress (e.g., up arrows for improvement, down arrows for deterioration) can make the results easier and faster to understand. The results can also be displayed as an e-portfolio, where each participant can access a personal profile showing progress in the development of competencies, where they can monitor their results and possible improvements in the areas in which they have been trained.

The progress report allows individuals to reflect on their strengths and areas for improvement and where they can focus on further growth. The progress report serves as positive reinforcement, encouraging participants to stay engaged in their learning journey and continue developing their skills. To this end, the DECIDE project also prepared an individual progress report for each participant, which was sent to their e-mail after the training. Such a report, detailing the development of competencies that the individual developed during their various training courses, can be a valuable addition to a young person's curriculum vitae (CV). For example, the automated report that an online tool can generate from such self-evaluations of self-learning can be attached to job applications, presented to recruiters at job interviews, or used to find further training opportunities. Such a report provides concrete evidence of the development of competencies and knowledge acquired and the individual's commitment to lifelong learning. All this provides additional positives when looking for a first job and makes individuals more attractive to potential employers.

Based on the feedback given by the participants, it can be concluded that most participants had a positive experience using the e-guide and the web application to evaluate the progress of their knowledge and skills during self-directed learning. The feedback highlights several strengths and areas for improvement, offering valuable insights into the tools' effectiveness. Many participants found the process engaging, educational, and interactive, with several emphasising the usefulness of pre-tests and post-tests and the ability to explore new topics. Positive comments included mentions of the appealing design, the opportunity to deepen knowledge, and the enjoyable learning experience. Most participants expressed satisfaction with the application, especially with the results displayed and the possibility of checking pre-tests and post-tests. Participants mentioned that they had learnt a lot and that it had been interesting to participate in the testing. Some participants expressed that they had learned things they had not known before, which shows the programme's educational value. Some stressed that the topic was interesting, that they enjoyed the learning process, and that they gained new information. Most agreed that the tool worked well, but some users suggested improvements, such as reducing the amount of information presented, adding interactive elements such as games or puzzles to enhance engagement, and clarifying the app's functionality for first-time users. Some expressed that there was perhaps too much information, suggesting that a more straightforward presentation of the content could increase the effectiveness of the learning. Overall, the experience seems to have been positive, with some suggestions for improvement, especially regarding greater interactivity and clarity of content. This feedback underscores the tools' potential while providing concrete directions for refining user experience, enhancing interactivity, and ensuring accessibility for diverse user groups.

5.4. The Future Job Sector of Youth

Work values influence young people's career choices, guiding their attitudes, motivation, and preferences towards future careers [33]. For this reason, career counsellors and educational institutions should include work and personal values in career development programmes to help students align their personal values with their career aspirations. Some research also shows significant differences in career choice-making among students by gender [33]. For example, female students are more likely to face specific challenges such as hesitation, lower self-understanding, and regretting decisions, which may be the result of gender stereotypes and narrower career options compared to their male peers. It is undoubtedly important to consider these challenges in career counselling and to present and provide female students with a broader range of career options than they see for themselves. In addition, self-esteem and self-efficacy are important for decision-making, as students with higher self-esteem and higher self-efficacy can better overcome difficulties in making decisions about their future [34,35]. This is particularly important for students training to become classroom teachers, who play a key role in shaping future generations' sustainable knowledge, values, and skills. A recent study of Finnish classroom teachers found that improving self-efficacy beliefs related to teaching ethics, values, and systems thinking can significantly improve their sustainability competence, which is transferred to their students [36]. Overall, in career counselling, it is crucial to consider a student's social background, including their political, economic, and environmental situation, as these factors influence their psychological well-being and ability to make career decisions.

The preference for digital marketing over other job profiles in our study, as reflected in the answers of the training participants, may be influenced by several factors, particularly current trends in the labour market, work values, and the growing importance of digital technologies. Digital marketing is becoming an increasingly important component of business strategies due to the continuous shift towards online platforms and digital consumer behaviour. Younger generations, particularly Generation Z and Millennials, who drive online media, find roles in digital marketing to be exciting opportunities for dynamic future careers. The attraction may also stem from the visibility and accessibility of the profession, with many students more familiar with social media and content creation, which are central to digital marketing. The rise in platforms that blend entertainment, social interaction, and commerce also increases the need for professionals who can navigate these complex ecosystems.

Many articles indicate that digital marketing is an attractive career choice for young people due to its visibility and role in modern economies and alignment with entrepreneurial and creative aspirations. For instance, Makrydakis discusses how digital marketing significantly influences the attraction of students to higher education, making it a field young people recognise as impactful and aligned with their aspirations [37]. Furthermore, Masenya highlights the role of digital marketing as a pillar for job creation and economic growth, especially in the digital economy, making it an appealing career for youth aiming to tackle unemployment [38]. Albab and Munandar explore the involvement of youth in digital marketing to manage community enterprises, illustrating how the integration of technology and marketing appeals to entrepreneurial-minded young individuals while also being supported by government initiatives [39]. Policymakers and educators can use these insights to further develop curricula and training programmes, thus ensuring that young people have the skills and competencies to succeed in this field.

To develop the necessary competencies for less popular occupational profiles such as biotechnology or IT, targeted educational measures should focus on raising awareness of these fields and their relevance to future challenges. In biotechnology, training could include practical modules on sustainable food production, environmental solutions for waste reduction, and biomedical innovations that align with global sustainability goals. In IT, programmes could emphasise advanced coding, cybersecurity, and artificial intelligence applications and highlight their transformative impact on industries. Collaboration with industry leaders, researchers, and universities can provide insights into market needs, and career advice can clarify possible career paths in these fields.

6. Conclusions

Considering the results of the e-guide and web-based application testing, combined with participants' feedback, this study highlights several positive aspects of the developed DECIDE digital tool. Participants consistently emphasised the clarity of the presentation of the result, demonstrating the application's effectiveness in visualising competency development progress and learning improvements. They also gained valuable new knowledge, confirming that the self-learning programme has an educational potential for career competency development. Furthermore, participants described the testing process as engaging and enjoyable, underscoring the value of an interactive and game-based learning approach. Notably, the relevance and attractiveness of the tool content were evident from participants' interest in career choices.

Despite these successes, the study identified areas for improvement to optimise the web-based application and e-guide content. At the beginning of each module, the objectives and expectations should be clearly defined, and participants should clearly understand those expectations. Adjusting the level of complexity, providing clear and simple content, and breaking information into smaller, precise units could address the issue of too much information. Clear and simple instructions to help with initial navigation through the e-guide and app, including short video instructions, could improve the user experience. Increasing interactivity through additional games and integrating gamification features could further motivate participants and enrich the user experience. Additionally, incorporating post-module feedback mechanisms and detailed explanations for incorrect answers in post-tests would provide more valuable learning opportunities. These improvements could further enhance the effectiveness of self-learning and self-assessment and improve the user experience.

The DECIDE tool is particularly beneficial for young individuals between 18 and 25 navigating critical career decisions, considering their skills, interests, and the demands of a changing labour market. Educational institutions can utilise such tools to support students in selecting study fields and professions, while career counsellors can integrate them into guidance frameworks. Using such tools is also appropriate for individuals who want to explore different options in the labour market and those who want to understand their career prospects better. Furthermore, the tool's value lies in promoting self-directed learning and self-assessment, empowering individuals to take responsibility for their professional and personal growth. It helps individuals carry out a personal SWOT analysis of themselves, i.e., discover one's strengths, weaknesses, opportunities, and barriers to success. Self-directed learning through self-evaluation is especially crucial in preparing young people for rapid technological changes that redefine the skills in modern workplaces. Lifelong learning is essential, and tools such as DECIDE help instil a mindset of continuous self-improvement, which is a key factor for career progress. In addition to all its advantages, when using a tool such as the DECIDE, it is important to consider its limitations and the impact of various factors on interpreting the results.

Further research should focus on refining the competency development monitoring tool to better support the monitoring of sustainability competency development. Within ongoing Erasmus+ projects (IGNITE, Greenlead), efforts will include integrating sustainability and entrepreneurship into science, technology, engineering, and mathematics (STEM) study programmes, developing learning modules for platforms popular with young people such as TikTok and YouTube, and optimising the tool for tracking competencies such as green leadership. Enhancements such as gamified elements and expanded interactivity will further align the tool with the needs of young users navigating dynamic job markets. Such innovations will enhance self-directed learning and contribute to creating more effective career development tools, enabling educational institutions to serve as key drivers of sustainability and lifelong learning.

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Data Availability Statement: All presented data are available at Jožef Stefan International Postgraduate School, which has the project partner role in the DECIDE project. Participation in the survey for training participants was completely voluntary and guaranteed complete anonymity. The data collected was processed and presented at the aggregated DECIDE project level, without the possibility of identifying individual respondents. All data collected (responses) are recorded exclusively in the DECIDE database.

Conflicts of Interest: Author Marika Prucnal participated in the DECIDE project under the organization Stowarzyszenie IMPAKT from Kielce, Poland. She is not employed by the organization but collaborates with them under a different type of contract. Stowarzyszenie IMPAKT, which is a non-governmental organization, also served as the project coordinator. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Article

A Portfolio of Building Solutions Supporting Positive Energy District Transition: Assessing the Impact of Green Building Certifications

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Abstract: Positive Energy Districts (PEDs) represent an innovative approach to thinking and designing cities sustainably, in compliance with the European Union energy strategy. This strategy integrates sectors such as urban planning, energy, and construction to synergistically address energy and environmental challenges. Studies on sustainability assessment systems applied in PEDs evidenced that they focus mostly on energy aspects, while few include a comprehensive life cycle assessment of equivalent CO_2 emissions, considering the building component and the impacts of the materials used. Additionally, most assessments are conducted on the urban and district scale, such as Neighborhood Sustainability Assessments (NSA), which begin to correlate PEDs with the dynamics of selecting sustainable materials for green-certified projects, analyzed throughout the entire life cycle, relying on the adoption of Green Building Rating Systems (GBRS) at the building scale. To explore the impact of environmentally friendly (i.e., 'green') GBRS certifications in the selection of building materials and products according to sustainability criteria, and to encourage their use in projects explicitly referring to PEDs, this study analyzes the technical solutions implemented in two significant residential building renovation projects in Italy from a PED perspective. It proposes a classification system based on the required targets of energy efficiency, energy production, and energy flexibility. The results include the definition of an expandable portfolio of technical solutions, an analytical comparison between the materials used in the energy renovation projects of the case studies examined, and the sustainability criteria provided by voluntary 'green' certification tools (GBRS). The collected evidence offers an operational framework that confirms the positive impact of GBRS certifications and the related selection of materials on sustainable urban development, contributing to the scientific debate on PEDs. Furthermore, the use of voluntary 'green' certifications at the building scale can be encouraged in the context of the transition towards PEDs, aiming to identify specific criteria and indicators for the selection of building materials to be integrated into future PED certifications. This aims to contribute to creating energy self-sufficient urban areas, focusing on sustainability, efficiency, and innovation, in line with global emission reduction and climate change mitigation goals.

Keywords: Positive Energy District; green building rating systems; technical solutions; building materials and products

1. Introduction

In the context of global urbanization, cities play a pivotal role in energy consumption and climate change, accounting for a substantial portion of global CO_2 emissions. However, they also drive economic development, contributing significantly to global Gross Domestic Product (GDP).

Global initiatives such as the 2030 Agenda, New Urban Agenda, and Paris Agreement outline strategies for sustainable urban development. In Europe, the "2020 Climate and Energy Package" and "2030 Climate & Energy Framework" provide guidance for climate action. The EU's long-term strategy aims for a climate-neutral EU by 2050, emphasizing district-level approaches such as Positive Energy Districts (PEDs).

According to the White Paper on the PED Reference Framework, "PEDs are urban areas or groups of connected buildings which produce net zero greenhouse gas emissions and actively manage an annual local or regional surplus production of renewable energy. They require integration of different systems and infrastructures and interaction between buildings, the users, and the regional energy, mobility, and ICT systems, while securing the energy supply and a good life for all in line with social, economic, and environmental sustainability" [1].

Thus, the transition to PEDs is a crucial goal to address global challenges such as climate change, environmental sustainability, and energy security.

Positive energy balance in PEDs must be guaranteed through the simultaneous achievement of three main "goals": energy efficiency, local energy production, and energy flexibility [1]. This paradigm, promoted by European initiatives such as the European Green Deal [2] and the Renovation Wave Strategy [3], which provide essential regulatory frameworks to support PEDs [4], involves a profound transformation of the built environment. This transformation encompasses the design of new buildings and, even more significantly, the renovation of existing ones.

The Renovation Wave Strategy, in particular, aims to double the rate of energy renovations to improve the energy performance of buildings, placing the principle of "Efficiency First" at the forefront. This principle prioritizes energy-saving measures over increasing energy production.

Within the PED transition, the concept of a "positive energy balance" must therefore be considered broadly, aiming for net zero greenhouse gas (GHG) emissions by including the sustainable use of construction materials in energy assessments [5].

The construction industry is one of the most impactful sectors in terms of energy emission and raw material consumption [6]. Therefore, improving the energy performance of buildings must be integrated with a sustainability-oriented and circular economy approach, favoring low-impact materials and conducting a comprehensive assessment of their life cycle (Life Cycle Assessment, LCA) to ensure the environmental balance of building renovations within PEDs.

Indeed, the new Energy Performance of Buildings Directive also introduces carbon footprint assessments based on LCA, to be included in Renovation Passports for existing buildings [7].

The consideration of the environmental impact of construction materials in building construction or renovation projects, and the subsequent need for an LCA methodology to support their selection during the early design stages, is a well-established topic in scientific research [8,9]. This issue is addressed not only at the building level but also on a broader scale, such as neighborhoods [10,11].

The selection of sustainable materials is a complex process that requires considering various parameters throughout the building's life cycle to achieve green building certification [12]. In this context, a building's energy efficiency must be enhanced by utilizing low-impact or renewable natural resources [13].

The maturity of material selection processes in new constructions or building renovations is also evident through the observation of major green building rating systems (GBRS). Most of these systems include the selection of low-impact materials as part of the sustainability criteria for the building life cycle.

1.1. Neighborhoods Sustainability Assessment Tools and Material Selection Criteria

Despite the absence of specific certification protocols for Positive Energy Districts (PEDs), existing urban sustainability assessment tools represent a valuable starting point for addressing sustainability challenges at the district level [14].

The ISO/TR 37121 [15] and a report produced within the PED-ID project [16] map numerous systems for assessing the sustainability of urban and district-level interventions, known as Neighborhood Sustainability Assessment (NSA) tools [17,18].

Many studies have focused on comparative analyses of these tools, identifying their strengths and areas for improvement [19–26].

Specifically in the context of PEDs, Volpatti et al. [14] analyzed protocols such as LEED for Neighborhood Development (LEED-ND) [27], BREEAM Communities [28], and CASBEE for Cities [29], proposing the integration of additional criteria tailored to PEDs. These include surplus energy management, innovative business models for energy communities, and the evaluation of nature-based solutions.

Haase & Baer [30] examined two sustainability frameworks for PEDs, namely the "2000 W Site (2000 WS)" proposed in Switzerland and the "Zero Emission Neighborhood (ZEN) concept" developed in Norway. They related these frameworks to the concept of planetary boundaries, highlighting the environmental limits that must not be exceeded to prevent irreversible global changes. The same study underscored the importance of key performance indicators (KPIs) related to construction materials, including total greenhouse gas (GHG) emissions, lifecycle emission neutrality, and the adoption of sustainable materials based on circular economy principles, evaluated through Environmental Product Declarations (EPDs). These indicators are critical for adhering to planetary boundaries associated with climate change and land use.

Guarino et al. [31] discussed the state of the art in sustainability assessments for PEDs, emphasizing environmental, social, and economic applications. Among the key environmental KPIs, the study highlighted direct emissions, lifecycle indicators (LCA), and those linked to circular economy strategies. It also pointed out that the range of lifecycle indicators should encompass air pollution generated along the material supply chain.

The literature highlights a frequently overlooked issue: the accounting of indirect carbon emissions, which is often limited to the operational phase in the definition and assessment of PEDs [31]. This omission risks producing carbon balances that are far from realistic, undermining the achievement of true carbon neutrality. The embodied energy of construction materials is a critical factor that demands greater attention when evaluating the energy performance of buildings and districts to achieve effective urban decarbonization [32].

A more specific evaluation of material selection criteria in NSA tools was conducted by Yoon & Park [19], who examined BREEAM Communities [28], LEED-ND [27], and CASBEE-UD [33], along with four urban design guidelines. They structured a framework for material sustainability indicators based on the three pillars of sustainability—social, environmental, and economic—and categorized them by application domains such as landscape, infrastructure, and buildings.

For this article, focusing on the "buildings" domain, a review of indicators related to material selection at the urban scale was conducted, as summarized in Table 1.

Table 1. Indicators related to material selection at district scale.

NSA	Category	Criteria	Requirements
LEED v4 for Neighborhood Development (2018)	Green infrastructure and buildings	Certified Green Buildings	Design, build, or retrofit at least one building in the project or a portion of the total floor area to meet LEED certification or a similar green building rating system reviewed by an independent third-party accredited to ISO standards
		Recycled and Reused Infrastructure	Ensure that at least 50% of the total mass of infrastructure materials comes from a combination of post-consumer recycled content, on-site reused materials, and half of the pre-consumer recycled content. This applies to roadways, parking lots, sidewalks, curbs, water retention tanks, base materials, and utility piping (e.g., rainwater, sewer, or energy distribution). Recycled content must meet the ISO/IEC 14021 [34] standards for environmental claims
BREEAM Communities (2012)	Resources and energy	Sustainable buildings	The developer and design team committed to designing new or renovated buildings on-site to meet industry best practices in sustainability, focusing on energy, water, waste, material impacts, and occupant health and well-being
		Low impact materials	Contractors and sub-contractors must have environmental management systems, like EMAS [35] or ISO14001 [36], to ensure sustainable material management in the public realm [1]. Credits are awarded based on the percentage of materials used that achieve an A+ to B rating in the Green Guide to Specification
CASBEE-UD (2014)	Resources recycling—Construction	Wood Material	Utilization level of wood materials produced from sustainable forests
		Recycled Material	Average usage of certified recycled items in a building in the block

[1] This issue does not cover the use of materials in the buildings themselves.

This review revealed that the observed NSA tools primarily focus on reducing the environmental impact of materials in public space design, while the proper selection of materials at the building scale is often left to the presence of green-certified buildings.

1.2. Green Building Rating Systems and Material Selection Criteria

At the building scale, Green Building Rating Systems (GBRS), including Leadership in Energy and Environmental Design (LEED) and the Building Research Establishment Environmental Assessment Method (BREEAM), represent the most established frameworks for evaluating and certifying the ecological and environmental performance of buildings [37,38]. These protocols also include specific criteria for material selection based on sustainability principles.

Since 2008, European policies, through the adoption of Green Public Procurement (GPP) [39], have stressed the importance of integrating environmental criteria into public procurement processes. Some national legislations have made GPP criteria mandatory. In Italy, for instance, the legislator adopted the Minimum Environmental Criteria (CAM) for 18 product categories, including construction, to achieve strategic objectives such as resource efficiency and conservation, waste reduction, and the minimization of hazardous substance emissions [40].

The same decree [40] recognizes the importance of GBRS as tools to demonstrate compliance with established environmental requirements. Specifically, the decree lists both national and international energy and environmental sustainability protocols, including LEED [41], BREEAM [42,43], and KlimaHaus Nature [44]. This approach allows designers to streamline the verification process, using certifications as evidence of compliance. However, it is essential that the documentation demonstrates adherence to all relevant environmental requirements, ensuring alignment between GBRS and the standards mandated by CAM.

In the literature, numerous studies compare different GBRS [8,45–49]. For instance, Park et al. [8] examine how various systems evaluate material-related aspects, while Braulio-Gonzalo et al. [50] analyze the coverage of the three dimensions of sustainability (environmental, social, and economic) and their relationship with the life cycle stages proposed by the EN 15978 standard [51].

A more detailed analysis of LCA methodologies within GBRS was conducted by Izaola et al. [52], which evaluate how five major European schemes integrate LCA into their certification processes. The study highlights significant differences in the adopted methodologies, undermining the comparability of results, and emphasizes challenges such as the lack of standardized data, the complexity of LCA calculations, and the need for specialized training.

To address these issues and provide a unified methodology at the European level, the Level(s) framework, promoted by the European Commission, offers a set of reference indicators to monitor and improve building sustainability throughout their entire life cycle [53].

A review of potential criteria and indicators for material selection at the building scale is summarized in Table 2.

This review highlights several recurring selection criteria. These include reducing greenhouse gas emissions by calculating global warming potential (GWP) and other LCA parameters; prioritizing (or mandating) the use of third-party-certified materials that adhere to environmental standards for sustainable sourcing and production; minimizing emissions related to transportation from production sites to construction sites; using reclaimed, recycled, or recyclable and durable materials; and excluding highly polluting or toxic materials, non-recyclable materials, and those that fail to comply with waste management regulations.

However, despite the widely recognized importance of selecting eco-compatible products and verifying their environmental impact through EPDs based on LCA principles, most evaluation tools, particularly in the context of PEDs, predominantly focus on energy-related aspects. Only 7% conduct a full life cycle assessment of CO_2-equivalent emissions [57].

While GBRS are widely acknowledged as valuable by the market and numerous models and tools are available, their application at the district level remains limited [58].

Table 2. Indicators related to material selection at the building scale.

Gbrs/Protocols	Category	Criteria/Indicator/Credit	Requirements
BREEAM Domestic Refurbishment (2014)	Materials	Environmental impact of materials	Assess the embodied impact and thermal performance of roofs, walls, windows, and floors using the Mat 01 calculator [1], based on the Green Guide rating of new materials and their contribution to thermal efficiency
		Responsible sourcing of materials	All new timber must be legally sourced and assessed with the Mat 02 calculator [1] based on responsible sourcing levels. Additional credits are available for having a sustainable procurement plan
		Insulation	New insulation in walls, floors, roofs, and building services must meet minimum assessment requirements
BREEAM International Non-Domestic Refurbishment (2015)	Materials	Environmental impact of materials	Reduce the building's life cycle environmental impacts by reusing materials and analyzing the impact of new materials using reliable life cycle assessment tools for the mail-building elements
		Responsible sourcing of materials	Materials are sourced according to a sustainable procurement plan, ensuring key building materials are responsibly sourced to minimize environmental and socio-economic impacts
		Designing for durability and resilience	The building incorporates measures to reduce damage as well as wear and tear, with design and materials specified to limit degradation caused by environmental factors
		Material efficiency	Measures have been identified and implemented to optimize material use
LEED v4.1 RESIDENTIAL BD + C MULTIFAMILY HOMES (2020)	Materials and Resources	Building Life-Cycle Impact Reduction	Demonstrate reduced environmental effects during initial project decision-making by reusing existing building resources or demonstrating a reduction in materials use through life-cycle assessment. Achieve one of the following options: Historic Building Reuse; Renovation of Abandoned or Blighted Building; Building and Material Reuse; Whole-building Life-Cycle Assessment
		Environmentally Preferable Products	At least 70% (by weight or volume) of each compliant building component must meet the following criteria: - Contain at least 25% reclaimed materials (e.g., salvaged, reused, refurbished materials, including wood by-products like secondary manufacturing items or recovered wood). - Contain at least 25% post-consumer or 50% pre-consumer recycled content. - Wood products must be FSC-certified or an equivalent approved standard. - Bio-based materials must meet the Sustainable Agriculture Standard, pass ASTM D6866 testing, and be legally harvested. Leather and other animal-based products are excluded. - Concrete must include at least 30% fly ash or slag as a cement substitute. - Products should come from manufacturers participating in extended producer responsibility programs Building product disclosure and optimization (BPDO)—Use materials with verified environmental impacts disclosed through EPDs BPDO—Sourcing of Raw Materials: ensure materials are responsibly sourced BPDO—Material Ingredients: select products with transparency in material ingredient disclosure
		Construction and Demolition Waste Management	- Recycle or salvage nonhazardous construction and demolition materials. Calculations must be consistent (by weight or volume): Exclude excavated soil and land-clearing debris from calculations. Count materials used as alternative daily cover (ADC) and wood waste converted to biofuel as waste, not as a diversion. Other waste-to-energy processes are not eligible for diversion credits. For international projects, waste-to-energy systems may count as a waste diversion if they comply with the European Commission Waste Framework Directive 2008/98/EC [54], Waste Incineration Directive 2000/76/EC [55], and CEN EN 303 standards [56] for waste-to-energy - Diversion of waste materials - Reduction in Total waste generated

Table 2. *Cont.*

Gbrs/Protocols	Category	Criteria/Indicator/Credit	Requirements
KlimaHaus Nature (2017)	Environmental Impact of Building Materials	Material/products-related Parameters	- Non-renewable primary energy (PEI nr) - Acidification potential (AP) - Greenhouse effect potential (GWP100) - Durability of materials (time of use) - Distance of the production site (place of raw material extraction, processing, and supply) from the construction site;
		Bonus	- Presence of an ecological certificate from a third party
		Data source	- KlimaHaus Material database [2] - EDP
		Prohibitions	- List of materials not allowed [3]
Level(s)	1: Greenhouse gas and air pollutant emissions along a building's life cycle	Indicator 1.2	Life cycle Global Warming Potential (GWP)
	2: Resource efficient and circular material life cycles	Indicator 2.1 Indicator 2.2	Bill of Quantities, materials, and lifespans Construction and Demolition Waste (CDW) and materials
CAM-Italy	Technical specifications for construction products	Thermal and acoustic insulation [4]	Thermal and acoustic insulation must meet the following criteria: - Have CE marking. - Contain no Substances of Very High Concern (SVHC) per REACH Regulation, exceeding 0.1% by weight. - Must not use ozone-depleting (ODP) blowing agents (e.g., HCFCs). - Must not be made with lead-based catalysts during spraying or foam formation. - Expandable polystyrene must have blowing agents below 6% of the product's weight. - Mineral wool must comply with Note Q or Note R of Regulation (EC) No. 1272/2008 (CLP). - For materials listed in the table [5], they must include the minimum required recycled, recovered, or by-product content by weight.

[1] Mat 01 calculator and Mat 02 calculator are tools used in the BREEAM Domestic Refurbishment assessment to assign credits based on the sustainability and environmental impact of materials. [2] KlimaHaus Material database provides specific data on a range of construction materials, with a particular focus on environmental parameters. [3] The protocol provides a list of materials prohibited or not allowed for certification purposes. [4] Other criteria, omitted here for the sake of brevity, pertain to the following categories: emissions in confined spaces (indoor pollution); on-site mixed and ready-mixed concrete; prefabricated products in concrete, autoclaved aerated concrete, and vibro-compressed concrete; steel; bricks and clay products; wood-based products; partition walls, perimeter cladding, and suspended ceilings; masonry in stone and mixed materials; flooring; PVC windows and shutters; PVC and polypropylene pipes; paints and coatings. [5] The table is provided within the decree.

1.3. Objectives and Structure of the Article

This article aims to examine the impact of green building certifications and their material selection criteria within the context of the transition to PEDs, using a case study analysis.

Previous studies have analyzed PED case studies by classifying the adopted solutions based on technological factors, local circumstances, and planning and implementation processes [59]. Other research has compared case studies, highlighting key success factors, including technological solutions, local constraints, and the roles of public or private entities in the realization of PEDs [60]. A collection of technical solutions and best practices for PEDs is also included in the PED implementation guidelines developed within the Making-City project [61].

However, none of these studies have classified technical solutions based on the three distinctive PED targets: energy efficiency, renewable energy production, and energy flexibility. The main sustainability criteria found in GBRS, such as the use of materials with recycled content, the proximity of production sites to construction sites, and the presence of third-party ecological certifications, will be correlated with the technical solutions implemented to meet the three PED targets.

This study focuses on two main research questions:

1. What recurring technical solutions can support achieving the three PED targets (energy efficiency, renewable energy production, and energy flexibility), and which materials are most commonly used for these solutions?
2. To what extent do sustainability criteria influence the selection of materials used for these solutions?

The results of this research include the following:

1. The definition of a portfolio of technical solutions for the transition to PEDs, which can be implemented and updated over time;
2. A comparison between the materials used in energy efficiency interventions and the requirements established by the main GBRS.

Through this analysis, the article aims to make a significant contribution to the scientific debate on PEDs by offering an operational framework to align building renovation interventions with environmental certifications in the Italian context.

The paper is structured into four sections. In addition to this Introduction, Section 2 describes the research phases and analysis methods used to assess two PED case studies in Italy. Section 3 highlights the results of the case study analysis. Finally, Section 4 presents the conclusions in relation to the research questions and the outlined objectives, discussing the limitations and potential future developments of the study.

2. Materials and Methods

To conduct a survey of relevant PED projects in Italy, the PED Booklet [62] and the "PED Database" from COST ACTION PED-EU-NET [63] were consulted. A total of ten projects were identified within the municipalities of Bassano del Grappa, Bologna, Bolzano, Florence, Lecce, Milan, Parma, Rome, and Trento.

From this initial selection, specific projects were chosen based on criteria such as the type of building renovation interventions aimed at improving energy efficiency, the accuracy and completeness of the available technical and procedural documentation, and the essential condition that the interventions were effectively implemented.

In particular, the study focused on two projects that met the aforementioned selection criteria: the REPLICATE project in Florence (initiated in 2016 and completed in 2021) and the SINFONIA project in Bolzano (initiated in 2014 and completed in 2020) [64]. Both projects were outcomes of Horizon2020 PED initiatives.

These projects included interventions on a series of buildings identified based on their location (Table 3).

Table 3. The case studies within the two selected PED projects in Italy.

Florence-REPLICATE		**Bolzano-SINFONIA**	
Via Marche 3-5-11	Building 1 *	Via Palermo 74-76-78-80	Building 2 *
Via Liguria 6-10-14		Via Brescia 1-3-5; Via Cagliari 10-10/A	Building 3 *
Via Nave di Barozzi alle Piagge 13/1-4		Via Passeggiata dei Castani	
Viale Guidoni	New building	Via Similaun	
Via Torre Degli Agli	New building	Via Aslago	
Via Toscanini	New building		
Viale Giannotti Ex Longinotti	New building		

* Building selected for the case study.

For both projects, an investigation was conducted into the technical solutions used for the renovation of three residential buildings.

The specific objectives of this investigation were as follows:

- to highlight the findings derived from the analysis of building renovation interventions;
- to identify the construction characteristics of recurring technical solutions;
- to verify whether specific measures for the selection of eco-sustainable construction products, considering their entire life cycle, were adopted in the observed projects.

Regarding the latter point, the analysis revealed that, in the case of REPLICATE, the procurement documents for the execution of works did not explicitly express any intention to adopt protocols to limit the environmental impact of materials.

In contrast, the SINFONIA project followed the KlimaHaus protocol, and as part of the project development, a dedicated certification for interventions on existing buildings, "KlimaHaus R", was also defined [65].

However, this certification does not consider the impact of construction materials. Therefore, the characteristics of the products used were assessed in accordance with the KlimaHaus Nature protocol, which includes a section on the "Environmental Impact of Construction Materials".

Consequently, for the analysis of the selected SINFONIA and REPLICATE projects, the research activities included the following:

- an in-depth study, conducted through a document review, of the residential building renovation interventions and their summarized graphical representation (see Sections 2.1 and 3.1);
- the identification of technical solutions and products used for their implementation (see Sections 2.2 and 3.2);
- the evaluation of the identified construction products concerning the environmental sustainability criteria present in green building certification protocols (see Sections 2.3 and 3.3).

2.1. Analysis of Building Renovation Projects

The transition to Positive Energy Districts (PEDs) in the selected cities involves a fundamental shift in urban paradigms, particularly in planning for energy-efficient building upgrades, starting with the renovation of public social housing. Within the context of the two Italian PED projects, an array of technical solutions was implemented to enhance the energy performance of the building stock, leading to CO_2 reductions, economic savings, and a significant contribution to sustainable urban development.

To this end, three social housing renovation projects were selected. For the REPLICATE project in Florence, the renovation of a residential building on Via Marche ("Building 1") in the Le Piagge neighborhood was chosen [66]. In the SINFONIA project in Bolzano, two cases were analyzed: the first on Via Palermo ("Building 2") [67] and the second on Via Brescia ("Building 3") [68].

For each of the three building renovation projects, a technical data sheet was developed using a framework proposed in a previous publication [69]. Each sheet included general information such as construction timelines, project financing, and objectives. Furthermore, the specific technical solutions implemented in each building to address the three PED targets—energy efficiency, energy flexibility, and energy production—were documented.

2.2. Analysis of Construction Technical Solutions

Following the collection of the general set of technical solutions, those related to the energy efficiency target were categorized into the following types:

- external wall insulation;
- roof/terrace insulation;
- external window replacement.

This categorization facilitated the development of a portfolio of solutions, offering an overview of various intervention alternatives and enabling effective comparisons.

For each solution, the associated construction products were identified and analyzed. Each product was examined based on its technical characteristics, including material composition, dimensions, supply specifications, and performance. Furthermore, the analysis highlighted the presence of environmental product certifications and key attributes for evaluating product compliance with sustainability criteria from a life-cycle perspective, such as durability, environmental impact, and features related to installation and disassembly.

2.3. Comparison Between the Observed Building Products and Sustainability Criteria for Material Selection

As previously mentioned, the interventions carried out under the SINFONIA project adhered to the KlimaHaus R protocol, which is specifically designed to evaluate the energy performance of buildings undergoing renovation. However, this protocol does not account for the environmental impact of materials. Consequently, this study references the KlimaHaus Nature protocol, proposed by the KlimaHaus Agency, which is compatible with the existing certification framework.

The KlimaHaus Nature Technical Guideline, particularly in the section titled "Environmental Impact of Building Materials", introduces the ICC indicator. This indicator calculates the environmental impact of building materials and products used in the building envelope through a dedicated calculation program. The ICC indicator evaluates four parameters: Non-renewable Primary Energy (PEI nr), Acidification Potential (AP), Greenhouse Effect Potential (GWP100), and Material Durability (Time of Use, tu).

For specific values of environmental parameters, reference is made to data available in the KlimaHaus database. Where a material is not included in the database, similar materials are used as substitutes. If the product being evaluated has an EPD compliant with ISO 14025 [70] and EN 15804 [71], the certified environmental parameter values in the declaration can be directly input into the calculation program.

The calculation program assigns bonus points for factors such as the proximity of production, processing, and supply sites to the construction site; the use of materials with third-party environmental certifications (environmental product label Type 1 according to ISO 14024 [72]; and materials produced in facilities certified with the Klima Factory label. Additionally, the Guideline specifies materials that are not permitted for Nature certification, such as products containing ozone-depleting substances, plastics with heavy metals or organic tin compounds, and tropical wood lacking FSC or PEFC certification.

The KlimaHaus Nature indicators for building materials are summarized in Table 2 (see Section 1.2). Based on these criteria, the technical characteristics and product certifications contributing to the fulfillment of these requirements were highlighted in the data sheets of the materials used in the analyzed projects.

3. Results

The results of the analysis for the three selected case studies, namely Via Marche in Florence (Building 1), Via Palermo (Building 2), and Via Brescia–Via Cagliari (Building 3) in Bolzano, are illustrated below, following the methods and observation criteria described in Section 2.

For each building, the technical solutions implemented to achieve energy efficiency goals were examined, and the building products used were evaluated according to the KlimaHaus Nature protocol.

3.1. Outcomes from the Analysis of Building Renovation Projects

For Building 1 on Via Marche in Florence (Figure 1), in relation to the energy efficiency target, the interventions included thermal insulation of the building envelope and roof.

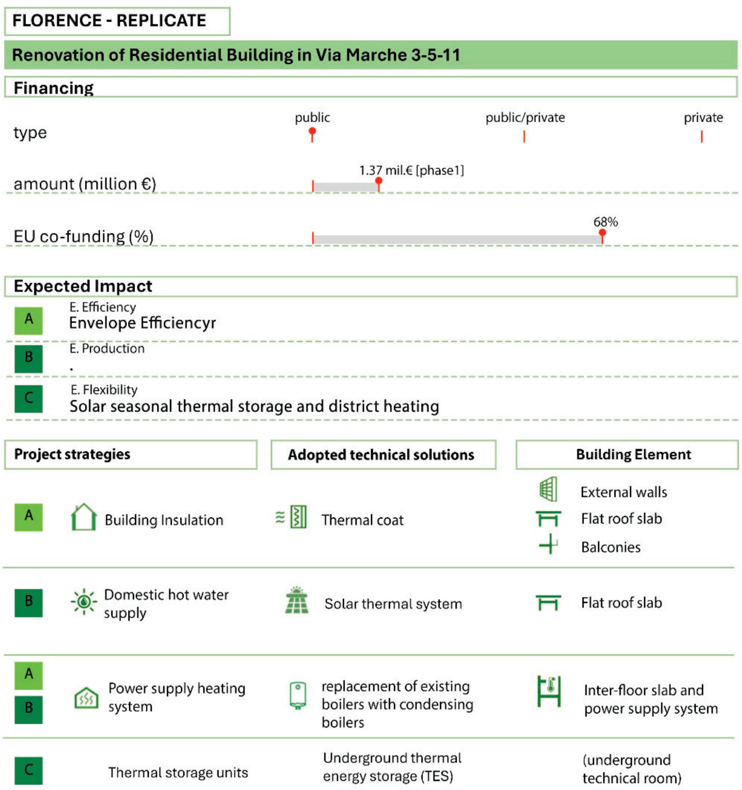


Figure 1. Summary sheet of technical solutions in relation to the three PED targets for Building 1 on Via Marche in Florence.

Active system solutions involved replacing existing heat generators with condensing boilers, upgrading the heating system, and transitioning from single-type heat generation systems to high-performance district heating systems.

In a subsequent phase of the project, the network will reach individual apartments, where the existing boilers will be replaced with small heat exchangers without disrupting service to tenants. This will benefit residents by reducing maintenance costs and energy consumption.

In terms of renewable energy production, heat will be generated by a cogeneration plant integrated with a solar system installed on the rooftops. A distinctive feature of the project will be the construction of an underground thermal energy storage (TES) unit to store energy for later use in heating (addressing the energy flexibility target).

In Bolzano, for Building 2 on Via Palermo (Figure 2), energy efficiency interventions included passive solutions such as thermal insulation of the building envelope and basement floor, replacement of external windows, installation of shading systems, and the construction of green roofs. Additional solutions involved the installation of mechanical ventilation (MV) systems under the window sills, the introduction of new shafts for the passage of utility ducts, and the rainwater collection system. Furthermore, regarding energy production, the project included the installation of photovoltaic panels and solar panels.

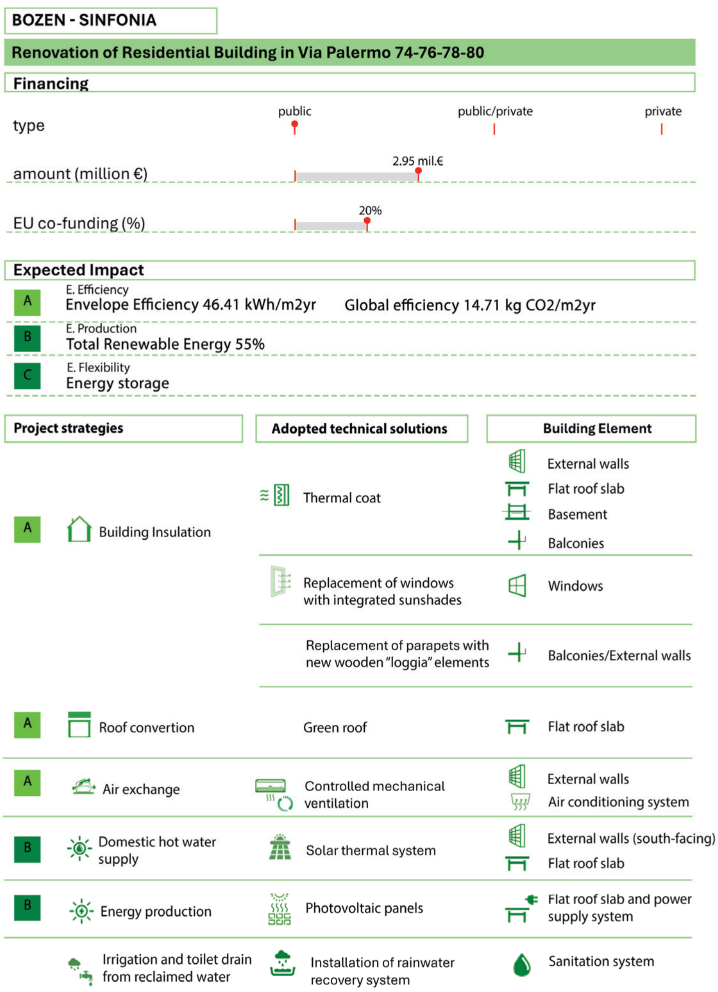


Figure 2. Summary sheet of technical solutions in relation to the three PED targets for Building 2 on Via Palermo in Bolzano.

For Building 3 on Via Brescia/Via Cagliari in Bolzano (Figure 3), passive solutions for energy efficiency included thermal insulation of the building envelope and basement floor, as well as the replacement of parapets and external windows. This project also involved the construction of a wooden elevation using the X-LAM building system. In all apartments, a decentralized mechanical ventilation (MV) system was implemented. Existing apartments retained their radiators, while radiant floor heating was installed in both the new apartments within the wooden elevation and the renovated existing apartments. Additionally, photovoltaic panels and a solar thermal system were integrated into the facade and roof, along with two thermal storage units connected to the district heating network, which is powered by the Bolzano waste-to-energy plant.

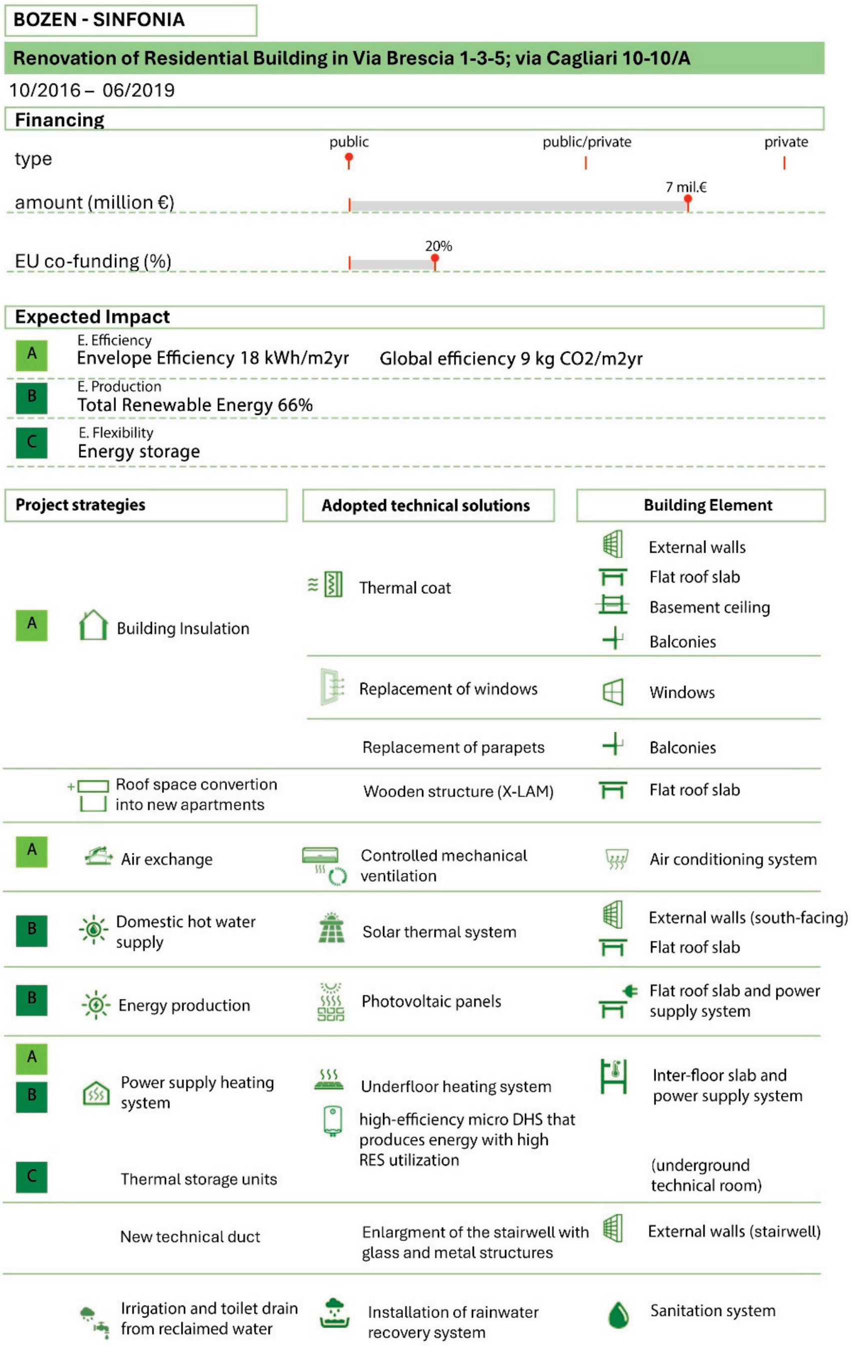


Figure 3. Summary sheet of technical solutions in relation to the three PED targets for Building 3 on Via Brescia–Via Cagliari in Bolzano.

3.2. Construction Features of Recurrent Technological Solutions

Focusing exclusively on passive strategies for energy efficiency, the most recurring technical solutions for envelope insulation were examined in detail.

For Building 1 (Figure 4), the facade insulation was achieved using expanded polystyrene panels with graphite, applied with a mineral binder adhesive and polyethylene sealants. The finish consists of pigmented plaster on fiberglass mesh with a double-polished anchoring base. Mineralized wood wool panels with the same finish were used to frame architectural profiles and window openings. For the terraces, the selected insulation panels were made of expanded polyurethane, combined with the installation of a waterproofing layer and new paving.

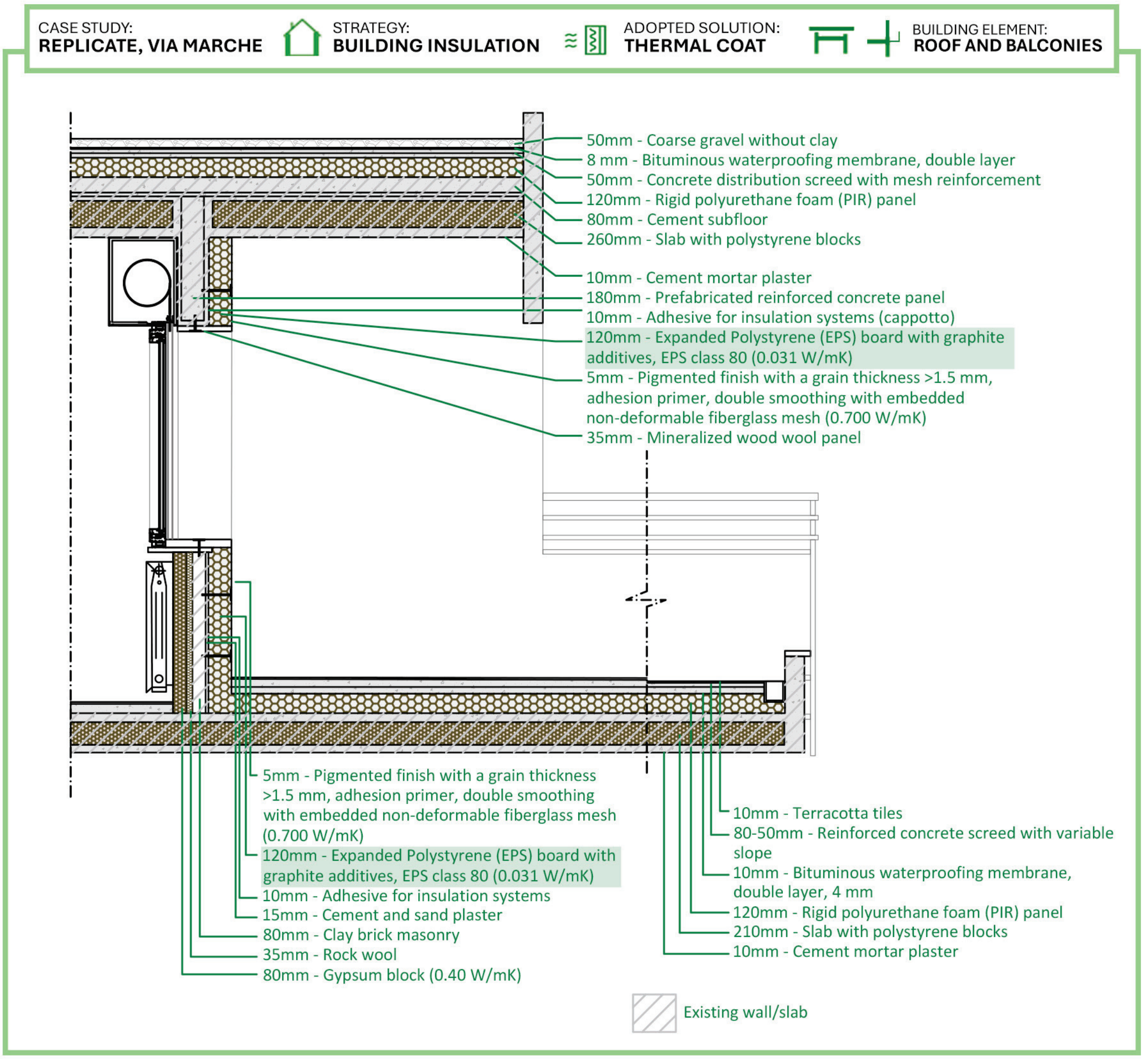


Figure 4. Exemplification of the portfolio of technical solutions for thermal insulation of Building 1 on Via Marche in Florence. Image edited by the authors from original drawings by © CASA SPA.

The intervention did not include replacing the windows but involved replacing the existing roller shutter boxes with new systems featuring integrated insulation.

For Building 2 (Figure 5), the design approach emphasized off-site prefabrication of components, rapid installation/easy disassembly, and the use of dry construction methods applied externally to the building to minimize disruption to tenants.

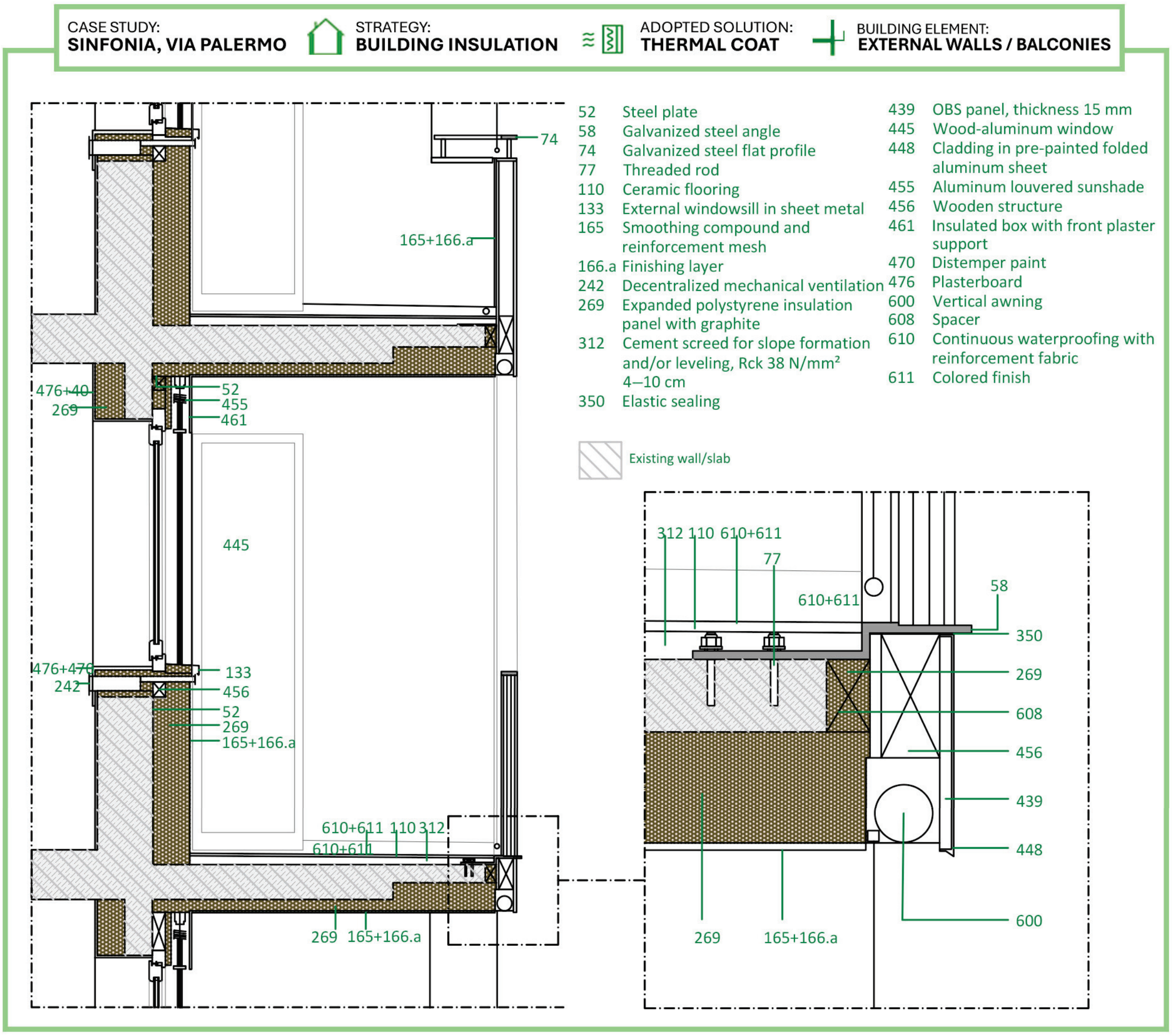


Figure 5. Exemplification of the portfolio of technical solutions for thermal insulation of Building 2 on Via Palermo in Bolzano. Image edited by the authors from original drawings by © Laboratorio di Architettura.

Specifically, window replacement was carried out by anchoring a prefabricated wooden structure to the existing concrete slabs visible on the facade. This structure comprised OSB panels with integrated thermal insulation in expanded polystyrene with graphite, wooden/aluminum windows with low-emissivity double glazing, and an aluminum slatted shading system.

The same system allowed for the integration of decentralized mechanical ventilation (MV) components below the windowsill, as well as external electrical wiring to power them. The external finish consisted of white stapled aluminum panels, while the internal finish was plastered drywall. A similar system was also used for the construction of new balconies.

For Building 3 (Figure 6), on the south-facing facade, the external thermal insulation system consisted of adhered rock wool panels covered by a windproof membrane, interspersed with wooden uprights to which the metal support structure for the solar collectors was anchored.

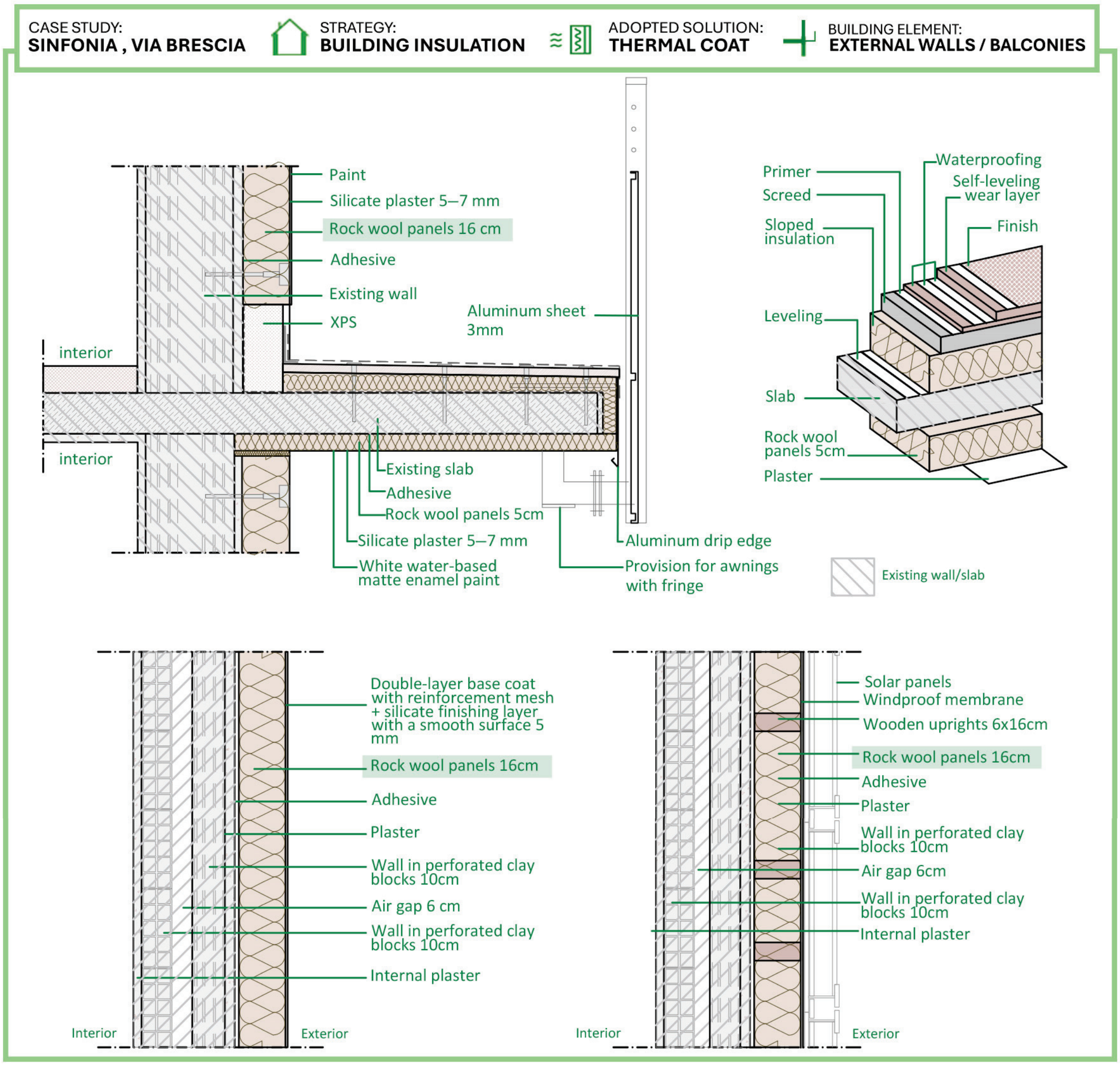


Figure 6. Exemplification of the portfolio of technical solutions for thermal insulation of Building 2 on Via Brescia—Via Cagliari in Bolzano. Image edited by the authors from original drawings by © Studio Tecnico Vettori.

On the other facades, the insulation panels were coated with a smoothing layer, a reinforcement mesh, and a finishing layer in silicate/siloxane paint.

The types of solutions identified were organized according to the involved building element and reported in a portfolio.

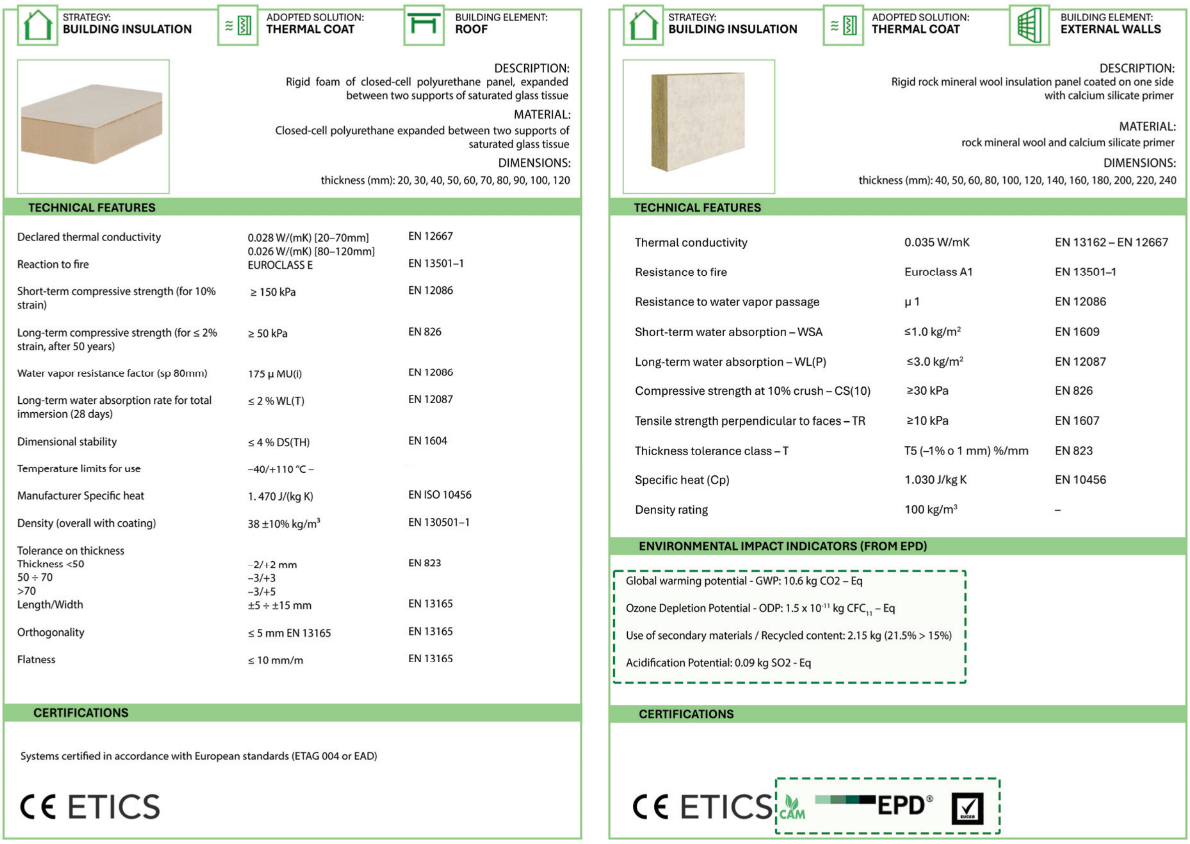
3.3. Compliance of Products with Material Sustainability Criteria

In the context of insulating the external envelope, detailed discussions focused on the construction products used for insulation panels.

In the case of Via Marche in Florence, adherence to ETICS regulations and certification in accordance with ETAG004 were mandated in the procurement documents [73]. For mineralized wood wool panels, eco-compatibility certification by ANAB-ICEA for both materials and production processes, as well as sourcing from sustainably managed forests (PEFC), was required. Expanded foam insulation components were specified to exclude ozone-depleting chlorofluorocarbons (CFCs or HCFCs). Accordingly, a compliant solution utilizing polyurethane panels for thermal insulation was documented in a technical sheet.

For the Bolzano projects, material selection was guided by the Technical Standards defined by the Institute for Social Housing of the Autonomous Province of Bolzano (IPES) [74]. The "Ecology and Sustainability" section emphasized the selection of materials and construction methods based on factors such as the use of renewable resources, low energy consumption during production and transportation, preference for regional resources and products, minimized or eliminated use of solvents, and the utilization of recycled or recyclable materials. Moreover, priority was placed on construction materials with low disposal costs.

To facilitate management during the use phase and component recovery at the end of life, the standards recommended durable products with low cleaning and maintenance requirements, clear differentiation of materials with varying lifespans, and designing structural elements, systems, facades, and finishes as separate components to enable easier recovery and restoration. Similarly, the technical features of the insulating rockwool panels retrieved from the Bolzano projects' technical documentation were summarized. A comparison of the two products is presented in Figure 7.



(**a**) (**b**)

Figure 7. Comparison of data sheets of insulation materials used and selection criteria for sustainable materials between (**a**) Building 1 Via Marche in Florence and (**b**) Building 3 Via Brescia–Via Cagliari in Bolzano.

The comparison revealed that in the Bolzano case study, the products align with the documentation required to verify compliance with the KlimaHaus Nature protocol. The Bolzano project serves as a notable example of environmental sustainability, showcasing a process where maximum transparency regarding material impact—mandated by product life cycle quality certifications—ensures higher quality technical solutions aligned with the philosophy of transitioning to PEDs.

4. Discussion and Conclusions

This study analyzed the role of green building certifications and material selection criteria in facilitating the transition toward PEDs. Through a document review and the examination of three Italian case studies—particularly residential retrofitting projects in Bolzano and Florence—key technical solutions were identified to meet PED objectives: energy efficiency, renewable energy production, and energy flexibility. The findings enabled a comparison of the construction characteristics of the adopted technological solutions with the criteria outlined in green certification systems, highlighting the relevance of voluntary protocols in supporting the environmental sustainability goals of PEDs.

Adopting criteria based on specific indicators proposed by these protocols was found to significantly reduce the environmental impact of building interventions, particularly through passive energy efficiency solutions. The Bolzano case, for example, illustrates how certifications like KlimaHaus can align with Italian regulatory frameworks, particularly the Minimum Environmental Criteria (CAM), enhancing transparency and traceability in material selection. This alignment strengthens the social and institutional credibility of PED-related interventions while supporting broader sustainability goals.

Green building certifications have evolved from simple acknowledgments to powerful tools for incentivizing sustainability. They raise awareness, influence design decisions, offer economic benefits, and foster energy performance monitoring. Furthermore, future PED-specific certification systems could integrate dedicated material selection criteria to promote greater sustainability. This study underlines the importance of adopting GBRS-based material selection criteria as a promising practice for ensuring sustainable and efficient interventions in energy retrofitting projects.

Despite these contributions, the study presents certain limitations. The analysis relied exclusively on documentary sources available in Italian, as the data primarily originated from local administrations and planners involved in PED projects. Additionally, the number of case studies was limited, reflecting only a partial view of the diverse international experiences related to PED transitions. Lastly, the study focused on insulating materials, leaving room for further exploration of other building components.

Nevertheless, this research revealed several key insights. To facilitate the transition toward PEDs, it is advisable for building interventions to follow GBRS criteria in material selection. Certification protocols can play a significant role in energy retrofitting projects by increasing the likelihood of employing sustainable materials. Future PED-specific certification systems should integrate criteria dedicated to material selection, further enhancing sustainability in such projects.

In conclusion, this study contributes to the scientific debate on PED transitions by offering a methodological framework that, with appropriate adjustments, could be extended to international contexts. Future research could expand the focus to include other building components, conduct comparative analyses with international examples, and refine material sustainability indicators for inclusion in future PED-specific certifications.

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Abbreviations

The following abbreviations are used in this manuscript:

AP	Acidification Potential
ANAB	National Association for Green Building Architecture
BREEAM	Building Research Establishment Environmental Assessment Method
BPDO	Building Product Disclosure and Optimization
CAM	Minimum Environmental Criteria
CLP	Classification Labeling and Packaging
CFC	Chlorofluorocarbons
CO2	Carbon Dioxide
EPD	Environmental Product Declarations
ETICS	External Thermal Insulation Composite System
EU	European Union
FSC	Forest Stewardship Council
GBRS	Green Building Rating Systems
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GPP	Green Public Procurement
GWP	Global Warming Potential
HCFC	Hydrochlorofluorocarbons
ICEA	Institute for Ethical and Environmental Certification
ICT	Information and Communication Technology
IPES	Institute for Social Housing of the Autonomous Province of Bolzano
KPI	Key Performance Indicators
LCA	Life Cycle Assessment,
LEEAD	Leadership in Energy and Environmental Design
MV	Mechanical Ventilation
NSA	Neighborhood Sustainability Assessment
ODP	Ozone Depletion Potential
OSB	Oriented Strand Board
PED	Positive Energy Districts
PEI nr	Non-renewable Primary Energy
PEFC	Program for the Endorsement of Forest Certification
SVHC	Substances of Very High Concern
TES	Thermal Energy Storage
ZEN	Zero Emission Neighborhood

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Physical–Mechanical and Microstructural Properties of Non-Autoclaved Aerated Concrete with Ash-and-Slag Additives

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Abstract: Non-autoclaved aerated concrete (NAAC) is gaining attention for its strength-to-weight ratio and sustainability benefits. Produced by incorporating a blowing agent into a binder, aggregate, and water mixture, NAAC offers a lightweight and porous construction material. Ash and slag waste (ASW), primarily composed of silicon, aluminum, iron, and calcium oxides, presents significant potential as a sustainable additive. However, industrial-scale processing of ASW still needs to be explored in Kazakhstan. This study evaluates the feasibility of utilizing ASW from the Ust-Kamenogorsk Thermal Power Plant to produce earthquake-resistant NAAC. Incorporating 31.5% ASW by weight optimizes compressive strength, achieving 2.35 MPa and significantly improving the mechanical properties. Chemical and microstructural analyses confirm ASW's suitability as a construction material. The study also introduces innovative processing methods and explores convolutional neural network models for predicting material structure changes, providing insights into optimizing production processes. The findings address the research objectives by confirming the viability of ASW in NAAC production and demonstrating its potential for sustainable construction. The results offer a pathway for industrial-scale applications, contributing to waste utilization and resource conservation.

Keywords: non-autoclaved aerated concrete; ash-and-slag waste; sustainable construction; microstructure analysis; artificial intelligence

1. Introduction

Kazakhstan's energy resources, a significant player on the global stage, are primarily composed of coal (46%) and uranium (29%), with oil and gas contributing less than 25%. The country ranks among the top 20 global producers of primary energy, generating around 157 million tons of oil equivalent annually. Coal is the primary fuel for Kazakhstan's thermal power plants, producing 85% of its electricity. It is widely available, affordable, and versatile, though its quality is relatively low due to high moisture, ash, and sulfur content. Most reserves are concentrated in central Kazakhstan, including major basins like Karaganda, Ekibastuz, and Maykubensk [1–3].

Over 80% of the coal burned in thermal power plants has a high ash content (40–50%), leading to significant environmental challenges. These include air pollution caused by ash, carbon, nitrogen oxides, and slagging of heating surfaces. Such emissions contribute to a higher environmental impact in Kazakhstan than many other regions. Addressing these challenges, particularly the efficient utilization of coal combustion by-products such as ASW, presents an opportunity for sustainable development in the construction sector. The potential for integrating ASW into NAAC forms the core focus of this study, aiming to mitigate environmental impacts while developing cost-effective and durable construction materials, thereby ensuring the economic viability of the solution.

Aerated concrete is a widely used engineered product in construction due to its lightweight properties and favorable strength-to-weight ratio. However, despite its advantages over other alternatives, the performance of aerated concrete, particularly under in-plane and out-of-plane seismic loads, remains to be determined [4]. Previous studies have investigated the seismic performance of infill walls made of aerated concrete, demonstrating that technical solutions can effectively isolate these walls from seismic deformations induced by frame systems. These findings highlight the potential for creating seismically safe aerated concrete walls.

Autoclaved aerated concrete (AAC) is popular worldwide as an infill material due to its lightweight nature, excellent insulation, fire resistance, and high durability. In Turkey, for instance, AAC accounts for over 20% of the infill wall market. However, past earthquakes have shown that the seismic performance of infill walls has often been inadequate, resulting in both economic losses and psychological impacts. To address this, there is a growing demand for wall systems that can withstand seismic events without sustaining damage. Research indicates that structural engineers can design reinforced concrete frame buildings in compliance with modern seismic codes, allowing these systems to behave with ductility under seismic loads.

Comparative studies have demonstrated that NAAC, when manufactured using high-quality factory equipment, can match or even exceed the performance of gas silicate blocks. Moreover, NAAC production is 20–30% more cost-effective than AAC due to more straightforward and less expensive manufacturing requirements. While AAC production necessitates large-scale facilities and costly autoclaves, NAAC can be produced in smaller setups with minimal equipment, making it a more accessible and economical alternative.

NAAC has garnered significant attention for its potential in sustainable construction. This lightweight, porous material is created by introducing foaming agents into a mix of binder, aggregate, and water. Innovative applications have further enhanced its performance. For example, using recycled AAC as a partial sand replacement has increased compressive strength by up to 16%, attributed to an improved tobermorite phase and crystalline morphology, with evident environmental and economic benefits [5]. Strength development in LC3-50-based AAC has also been linked to katoite and carbonation processes, with properties varying based on block densities between 500 and 700 kg/m^3 [6].

Substituting 4–16% of cement with microsilica (MS) in NAAC has improved compressive strength, peaking at 16% MS, alongside better thermal conductivity and a more refined microstructure [7]. Furthermore, the integration of machine learning techniques, particularly neural networks, has demonstrated high accuracy in predicting NAAC properties, highlighting the potential of ash-and-slag waste as a key component for earthquake-resistant construction [8]. Similarly, using fly ash (FA) and bottom ash (BA) as partial replacements resulted in improved compressive (12.687 MPa) and tensile (1.540 MPa) strengths, reinforcing the viability of industrial waste in lightweight concrete [9].

Natural pozzolana (NP) as a cementitious replacement (5–20%) has also been shown to improve durability and mechanical properties, with 15% identified as optimal for maximizing strength [10]. Additionally, reinforcing NAAC with plant fibers, such as sisal (SF) and coconut fibers (CFs), further enhanced compressive and bending strengths by up to 40% and 47%, respectively, while reducing density and thermal conductivity [11].

Other approaches, such as replacing up to 35% of fine aggregate with fly ash cenospheres (FACs), maintained strength within target limits while improving sustainability [12]. Modified desert sand (DS) in alkali-activated cement (AAC) demonstrated optimal performance at a 10% dosage, with compressive strength reaching 72.3 MPa [13]. Fiber-reinforced AAC panels offered improved mechanical properties and impact resistance, though brittle failure modes underlined safety considerations [14].

The authors of reference [15] proposed a composition of non-autoclaved aerated concrete based on hydrotreatment ash (ash-and-slag mixture) from Tverskaya TPP-4. This ash is ash of mixed character (approximately coal ash by 60% and peat ash by 40%). In literature sources, there is little information about using this type of ash as a silica component for aerated concrete. The obtained aerated concrete is characterized by a uniform, highly porous structure, an average density of D500 grade (465 kg/m^3), and strength class B1 (1.64 MPa). The calculated economic effect of aerated concrete production based on the results of the pilot batch production was 400 rubles/m^3.

The chemical composition of ASW is conditioned by the quality of coal burnt at power sources. It is represented mainly by silicon, aluminum, iron, and calcium oxides, which account for up to 95% of the waste mass. There are three main types of ash and slag. The first type is fine dry fly ash, formed during coal combustion and captured by electrostatic precipitators. The second type is slags. They are formed in the boiler; they are larger, non-combustible vitreous mineral particles. The third is ash-and-slag material. It is a mix of fly ash, bottom ash, and water, which is delivered to ash disposal sites in the form of pulp. Ash and slag have been globally recognized as reliable and safe building materials with diverse applications. For instance, in China, legislation prohibits the extraction and use of natural mineral resources in construction within an 80 km radius of a TPP ash dump, promoting the utilization of industrial waste. As highlighted in references [16–18], the current state of energy-efficient structures made from aerated concrete demonstrates the material's potential in residential construction. The study examines key properties of aerated concrete, including its composite nature, structural strength, and thermal performance. These findings underscore the importance of optimizing material properties to enhance energy efficiency and durability in construction. The analysis of existing problems of gas concrete production in the Republic of Uzbekistan is also presented. The research results on the use of industrial waste in aerated concrete have shown the expediency of continuing research on physical–mechanical and chemical activation methods for wide application of secondary activation of filler in construction production. The current state of construction of external wall structures of energy-efficient residential buildings from aerated concrete is presented, and the main properties of aerated concrete are analyzed.

The properties of composite building materials, including strength and thermal performance, are influenced by their structure. An analysis of existing challenges in producing aerated concrete in the Republic of Uzbekistan highlights specific regional issues, providing insights into how local conditions affect material production and performance.

In Russia, as in Kazakhstan, which has significant coal-based energy industries, high-calcium ashes are actively utilized in construction materials. However, their application remains challenging due to fluctuations in composition, variable properties, and the high content of free CaO [19]. These challenges necessitate the development of robust processing and quality control methods to ensure consistent results.

Efforts to optimize the production of NAAC have focused on two primary directions: varying the composition of the initial mixture and innovating production methods and equipment. For instance, researchers [20] have proposed using the Taguchi method and ANOVA test to systematically evaluate the effects of compositional variations, offering a valuable framework for achieving optimal material properties. The results showed that Portland cement, phosphogypsum, and quicklime positively affected the compressive strength of non-autoclaved aerated concrete. The composition of lightweight concrete using 34% Portland cement, 35% phosphogypsum, and 10% quicklime to obtain a compressive strength of 20.93 kg/cm^2 with an elasticity of 806 kg/m^3 was found to be optimum. The paper [21] presents the results of experimental studies of porosity parameters, strength properties, and properties of aerated concrete based on industrial waste. The constructively optimal amount of water reflecting physical–mechanical, thermal, and technical properties of exterior wall constructions based on aerated concrete was determined. The change in the properties of aerated concrete and the wastes of quartz sand and slag from steel-smelting manufacturing is investigated. Mathematical regression methods and determining materials' physical and mechanical properties achieve optimization of aerated concrete composition. The results of research on the automation of the calculation of the proposed composition of aerated concrete and the amount of industrial waste by its grades are given. NAAC has gained significant attention as a sustainable construction material due to its lightweight properties and cost-effective production process. However, the effective use of industrial by-products, such as ASW, in NAAC production remains underexplored, particularly in Kazakhstan. While existing studies have demonstrated the potential of ASW to enhance concrete's physical and mechanical properties, limited research addresses its industrial-scale application or examines its impact on earthquake resistance.

This research aims to bridge these gaps by evaluating the feasibility of using ASW from the Ust-Kamenogorsk Thermal Power Plant in NAAC production. The study also introduces innovative methodologies for analyzing and optimizing the material's microstructure, including digital technologies and convolutional neural networks. These approaches represent a novel contribution to the field, offering both theoretical insights and practical solutions for sustainable construction. By addressing the variability in ASW composition and its effects on NAAC properties, this research advances the understanding of sustainable material development and provides a framework for industrial application.

One of the main criteria for large-scale application of ash and slag materials is their complete environmental safety. It is established that ash-and-slag material complies with national and inter-national sanitary-epidemiological norms, rules, and hygienic standards [22]. It is completely safe, non-toxic and can be used not only in construction but also in the technical stage (planning, slope formation, backfilling of excavations and pits) of reclamation of disturbed lands, elimination of consequences of subsoil use, vertical layout of the territory and formation of intermediate insulating layers on landfills with household waste. Ashes from Krasnoyarskaya TPP-2 produce construction foam and gas blocks, paving stones, and asphalt.

Despite the significant possibilities of using ASW for the production of building materials and products of the widest nomenclature, including cement constituents, aggregates, wall materials, road construction, etc., and a considerable amount of research on their processing available in Kazakhstan and the world, ASW processing on an industrial scale is rarely carried out in Kazakhstan. The work aims to study the physical–mechanical and microstructural properties of ASW and non-autoclaved aerated concrete with ash and slag additives to develop a promising method of processing this type of waste.

2. Materials and Methods

The object of the study is ash from ash dump of boiler house No.2 of Ust-Kamenogorsk CHPP (Ust-Kamenogorsk city, Kazakhstan). This object was formed as a result of combustion of coal from the Karazhyra field, which is composed of D-grade hard coal (long-flame) with an ash content ranging from 12 to 25%, working moisture of 12–16% and volatile matter content of 47%. The lower heat of combustion of working fuel is in the range from 4500 to 5200 kcal/kg. The quality of mined coal is determined based on the results of advanced formation geological sampling of coal in the faces prepared for mining. Technical analysis of samples obtained via different methods of sampling was performed in the accredited laboratory of JSC "Karazhyra" [23].

Ash is a grey-black dust, which remains after coal combustion, and bottom ash is a solid molten residue and visually, it is black stones of a small size. After coal combustion in the boilers of power plants, the remaining ash and slag are removed, as a rule, with the help of water and taken to special storage sites, ash dumps. The ash is placed on the ash disposal area designed for the reception and storage of ash and slag waste. The view and location of the boiler house and ash dump are presented in Figure 1.

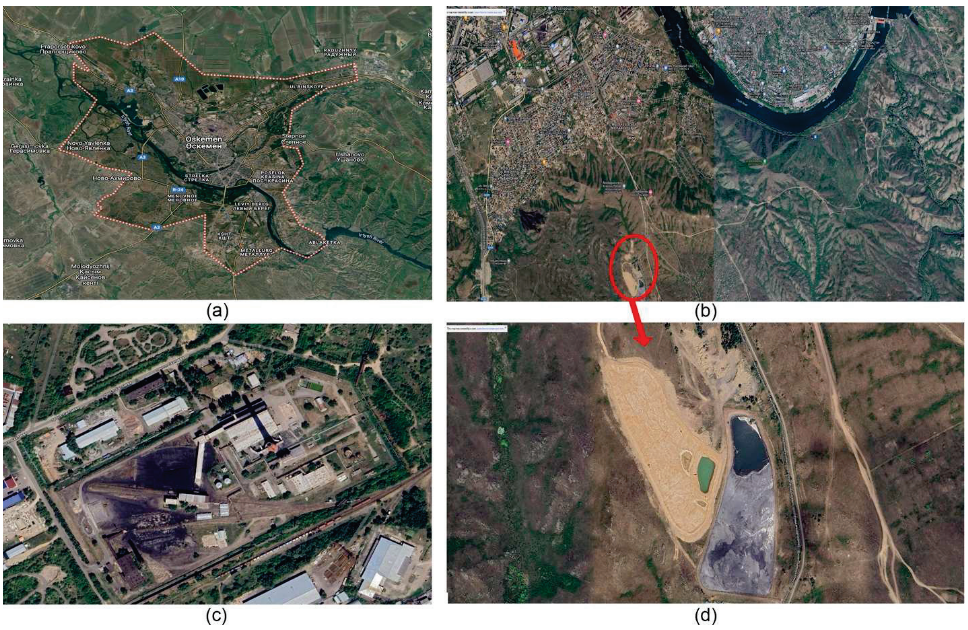


Figure 1. Overview of Ust-Kamenogorsk city and Ust-Kamenogorsk CHPP facilities (**a**) View of Ust-Kamenogorsk city. (**b**) General view of ash dump location with indication to the boiler house. (**c**) Enlarged view of boiler house No. 2 of Ust-Kamenogorsk CHPP. (**d**) Enlarged view of the ash dump.

Ash dumps are designed for long-term storage of ash and bottom ash that are in demand by consumers. Ash and slag are stored in the form of slurry in surface ash dumps (ASDs) or dry storages. In addition to waste mines and quarry workings, ravines can also be used as ash dumps. In the power industry of the Republic of Kazakhstan, surface ash ponds are mostly used. The appearance of the initial ash and slag is shown in Figure 2.

To conduct studies of microstructural properties of ash and slag washers, samples in the form of pellets were prepared (Figure 3). The initial powder sample was placed in a mould with a diameter of 30 mm, filled with epoxy filler, mixed, dried, and then the obtained product was ground and polished. To conduct studies of physical and mechanical characteristics of ash-and-slag concrete samples, the following methods were used (Figure 4).

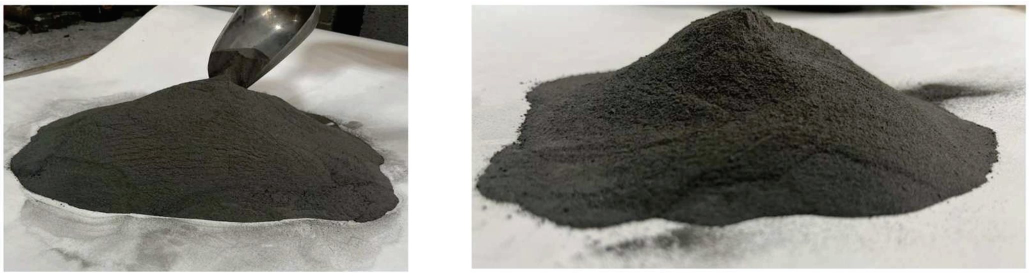
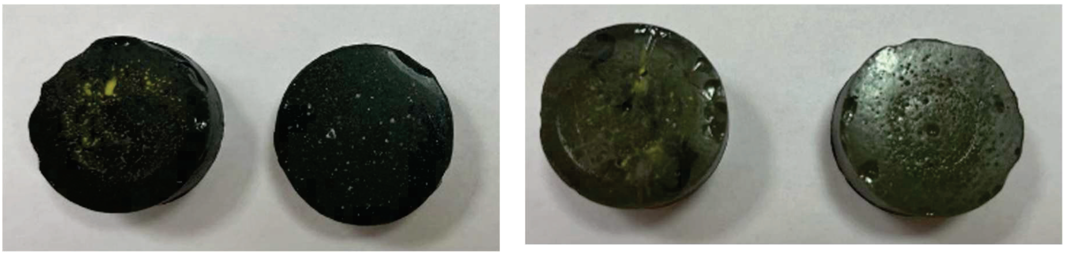


Figure 2. ASH samples from the ash dump of boiler house No. 2 of the Ust-Kamenogorsk CHPP.



(**a**) (**b**)

Figure 3. Samples for physical–chemical studies: (**a**) sample number 1; (**b**) sample number 2.

Figure 4. Aerated concrete samples.

To carry out this research, we used analytical and other equipment, including the X'Pert PRO MPD X-ray diffractometer. To determine the phase composition of samples, the method of X-ray diffractometry was used, with comparison of the obtained diffractograms using the X'Pert HighScore program, which utilizes the Crystallography Open Database (COD) and the Inorganic Crystal Structure Database (ICSD). Research conditions included a temperature of 23 °C, humidity of 51%, and atmospheric pressure of 100.1 kPa.

Determination of all physical and mechanical parameters was carried out according to the requirements of normative documents on test methods. Grain composition of ash-and-slag cement was determined according to EN 933-1 [24], the specific surface of fine-grained ash-and-slag cement and residue on sieve No. 008 was determined according to EN 196-6 [25], bulk density of ash-and-slag cement was determined in the dry state according to EN 1097-3 [26], and uniformity of volume change was carried out in a mixture with Portland cement at a ratio of 1:1 (cement:ash) according to EN 196-3 [27] by boiling samples in water. The results of physical and mechanical tests are given in Table 1.

Table 1. Physical and mechanical parameters of ash and slag.

Name of Indicators	Actual Values of Indicators
Determination of uniformity of volume change, mm	4.5
Humidity, %	0
Bulk density (specific gravity), kg/m^3	1140
True density, kg/m^3	2112
Specific surface (m^2/kg)	253
Particle size distribution, % on sieves (mm) from	from 2.5 to <0.16

The results presented in Table 1 summarize the physical and mechanical parameters of ash-and-slag cement, highlighting its suitability for further studies and applications in non-autoclaved aerated concrete production. The uniformity of volume change, bulk density, and specific surface values align with the required standards, providing a solid foundation for subsequent analyses.

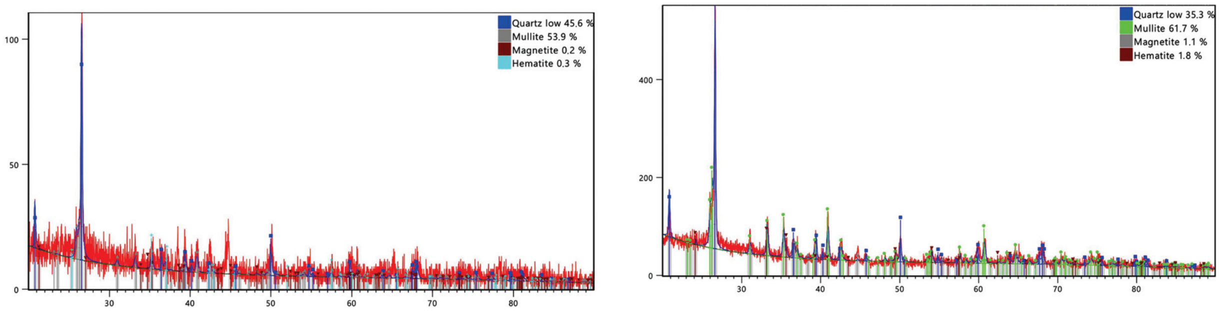
The results of studying the chemical composition of ash and slag are presented in Table 2.

Table 2. Chemical composition of ash and slag.

Sample Name	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	TiO_2	SO_3	$Na_2O{\cdot}K_2O$	Loss on Ignition
Ash-and-slag UK CHPP	51.27	22.49	9.32	2.95	1.69	0.95	0.93	4.67	5.63

The physical and mechanical characteristics and porous structure of aerated concrete with ash and slag additives were studied by X-ray diffraction analysis, scanning and optical electron microscopy. The spectra of ash and slag mixture samples obtained with the X'Pert PRO X-ray diffractometer (Figure 5) demonstrate that in all cases, the main components are oxides of silicon, iron and aluminium in the form of quartz, mullite, magnetite and hematite. The samples differ only in the amount of these or those minerals. In ash and slag from the ash dump, iron oxide compounds prevail and much fewer silicon oxides are reported. The main feature of ash and slag is the presence of the X-ray amorphous glassy phase in their composition. Glass formation is connected with the high temperature of solid fuel combustion, as a result of which natural quartz, a part of fuel, can melt, and lead to rapid cooling. Mullite is an aluminium silicate $3A1_2O_3{*}2SiO_2$, which is formed by high-temperature firing of silicates.

It is known [28] that fly ash is a heterogeneous material produced by the combustion of pulverised coal in thermal power plants and its phase and mineral composition include (i) an inorganic component, which is amorphous and crystalline; (ii) an organic component consisting of semi-coke (slightly altered, semi-coke and caked particles) and organic minerals; and (iii) a liquid component. Characterisation of fly ash is usually carried out using several techniques. However, scanning electron microscopy (SEM) is the best method and, along with X-ray diffraction, one of the most widely used methods for identification and characterisation of phases in fly ash, especially using SEM equipped with an energy dispersive detector. Ash exhibits variable composition and particle distribution depending on the sampling location. To investigate these differences, the samples were analyzed using a JSM-6390LV scanning electron microscope equipped with an INCA energy dispersive microanalysis system (Figure 6). Sample No. 1 represents a fresh ash-and-slag mixture directly from the furnace, while Sample No. 2 consists of aged ash-and-slag material collected from the ash dump.



(**a**) (**b**)

Figure 5. X-ray diffractometry spectra of ash and slag mixture: (**a**) fresh ash-and-slag sample from the furnace (current sample); (**b**) aged ash-and-slag sample from the ash disposal area (stored sample), (The red line represents the measured diffraction pattern, while the colored markers in the legend indicate the identified phases and their corresponding proportions).

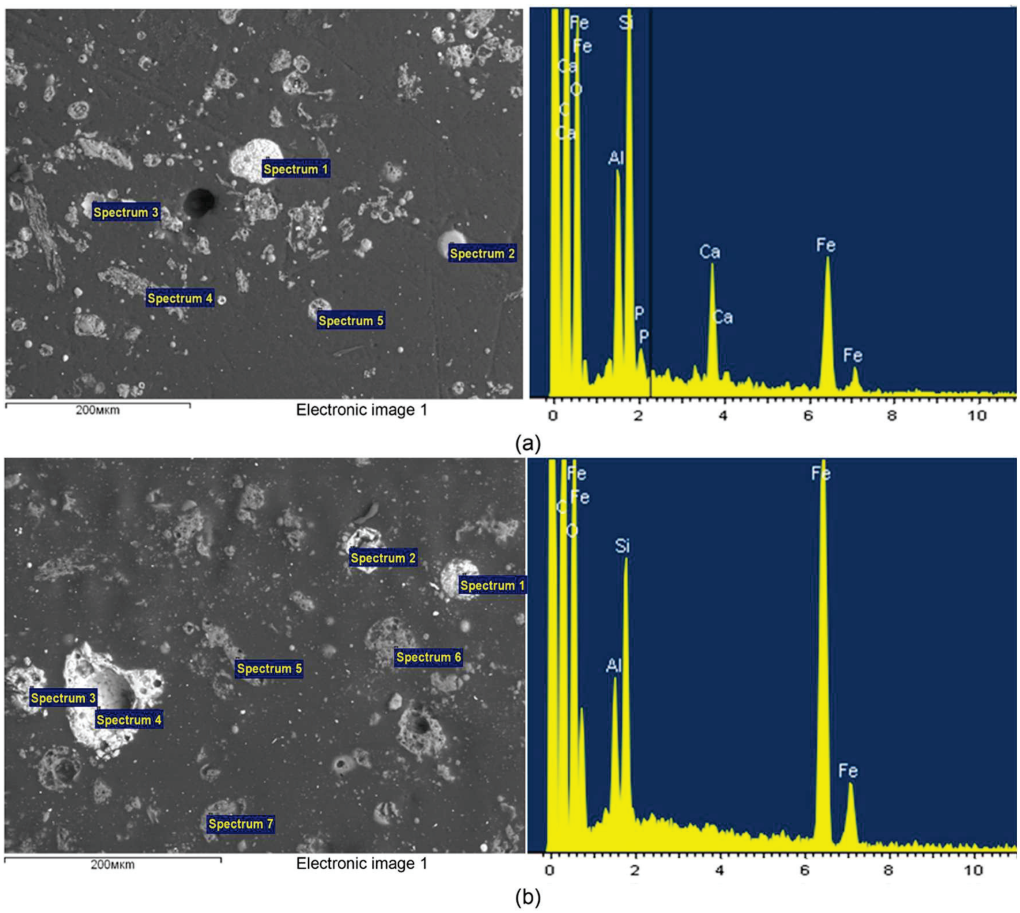


Figure 6. Images of ash and slag samples, obtained with a scanning electron microscope: (**a**) fresh ash-and-slag sample from the furnace (current sample); (**b**) aged ash-and-slag sample from the ash disposal area (stored sample).

The energy dispersive X-ray (EDX) analysis method was employed for elemental mapping of the samples. While EDX is limited to surface-level detection and cannot provide bulk compositional information, it is highly effective for identifying surface morphology and elemental distribution. These limitations highlight the need for complementary techniques, such as X-ray diffraction (XRD), to obtain a complete characterization of the samples. The choice of EDX is supported by its rapid analysis capability and precision in detecting key elements, making it particularly suitable for the preliminary assessment of heterogeneous materials like ash and slag.

The micrographs show that there are some differences in the surface morphology of the samples and the amount of the main constituents of ASW. In the current samples from the furnace, a relatively large number of coarse particles are found. They consist of coal, vitreous agglomerates and minerals (especially quartz). The SEM images of fly ash obtained can be used to describe the type of microspheres; however, only the composition and surface morphology can be evaluated using SEM techniques.

The authors of reference [29] proposed the use of image analysis using standard algorithms and artificial intelligence with both open source and commercial packages (such as ImageJ, Fiji or MATLAB). Recently, the application of neural networks provided increasingly effective image analysis and, among the different types of neural networks available today, the Self-Organising Maps (SOMs) of Kohonen seem to be among the most promising, given their capacity to receive many images as inputs and reduce them to a low number of neuronal outputs that represent all the input characteristics in a lower-dimensional space. We obtained a large series of images of ash and slag samples by means of studies on the Olympus BX-51 optical microscope with the Mineral C7 mineralogical analysis system (Figure 7).

Figure 7 shows the microstructure of aerated concrete samples with varying ash and slag content. It can be observed that increasing the ash and slag content from 25.5% to 31.5% improves pore distribution and enhances the material's strength [30]. The images obtained using a SEM clearly reveal denser and more homogeneous structures, explaining the increase in strength. These results confirm the effectiveness of using ash-and-slag additives in aerated concrete and their positive impact on the mechanical properties of the material.

The experimental samples of aerated concrete were prepared in the laboratory of the Competence and Technology Transfer Center in the field of construction at Serikbayev East Kazakhstan Technical University. Five different mixtures were prepared for the study, with ash-and-slag waste content varying from 25.5% to 31.5%. The main components used were Portland cement, quicklime, phosphogypsum, and a foaming agent. The mixtures were prepared according to established standards and methodologies, ensuring uniform distribution of additives throughout the mass.

The neural network model was developed using input data that included the chemical composition of ash-and-slag waste, specifically the content of oxides such as SiO_2, Al_2O_3, Fe_2O_3, and CaO; the percentage content of ash-and-slag waste in the mixture, ranging from 25.5% to 31.5%; the physical parameters of the samples, including density, porosity, and surface area; the results of mechanical tests, such as compressive and tensile strength values; and microstructural characteristics obtained using SEM and XRD, including pore size and distribution as well as the presence of crystalline phases. This data set was used for training and validating the Mask R-CNN neural network architecture to analyze and predict the microstructural characteristics of aerated concrete.

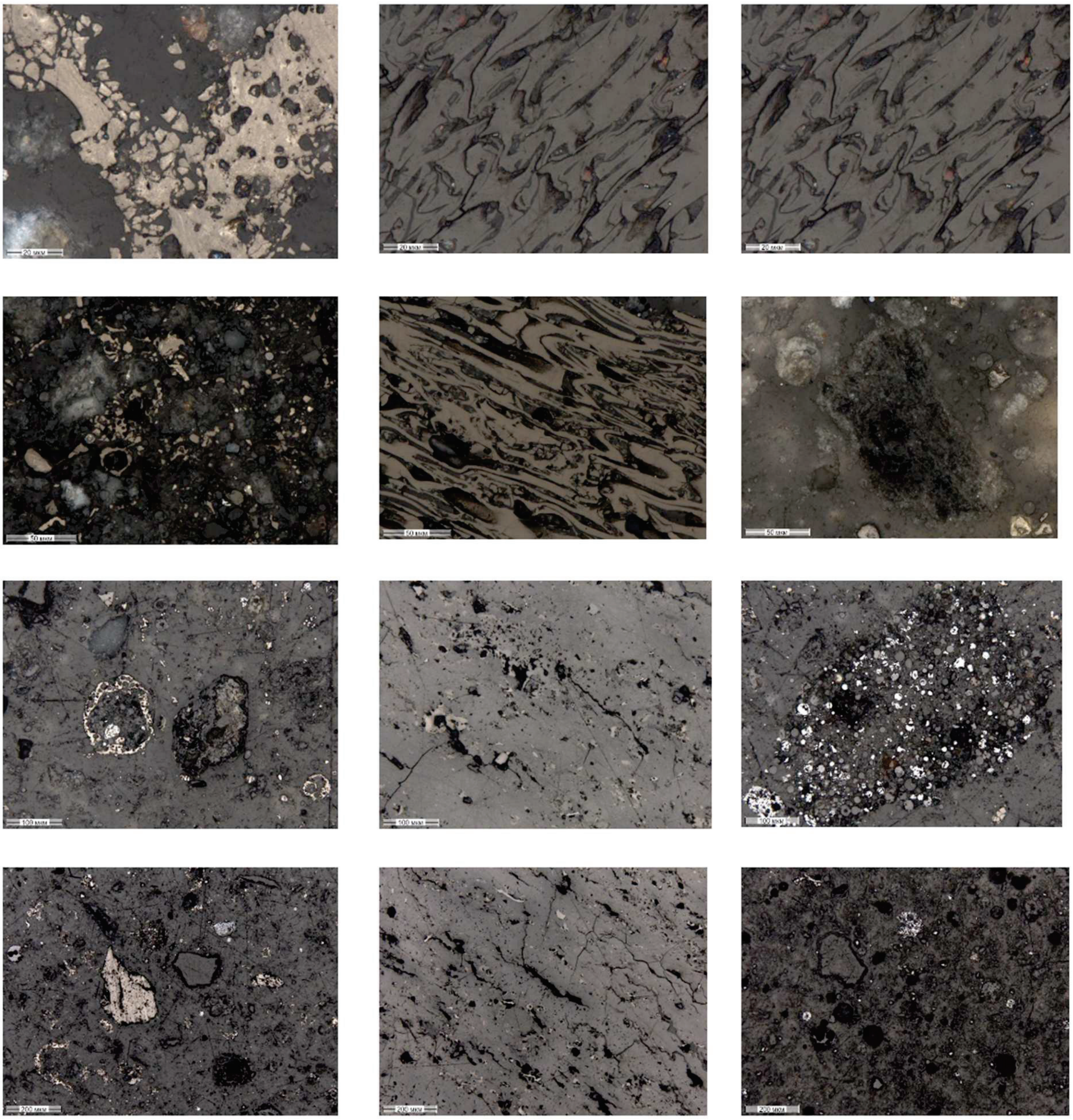


Figure 7. Images of ash and slag samples from the ash dump, obtained using an Olympus optical microscope at varying magnification from 20 to 200 µm.

3. Results

The effect of the amount of introduced ash-and-slag mixture on the compressive strength of aerated concrete is shown in Figure 8. The data presented in this figure were obtained from the experimental results of the present study, which involved testing various mixtures with ash-and-slag content. These findings are based on laboratory-scale experiments conducted to evaluate the relationship between ash-and-slag content and the compressive strength of non-autoclaved aerated concrete.

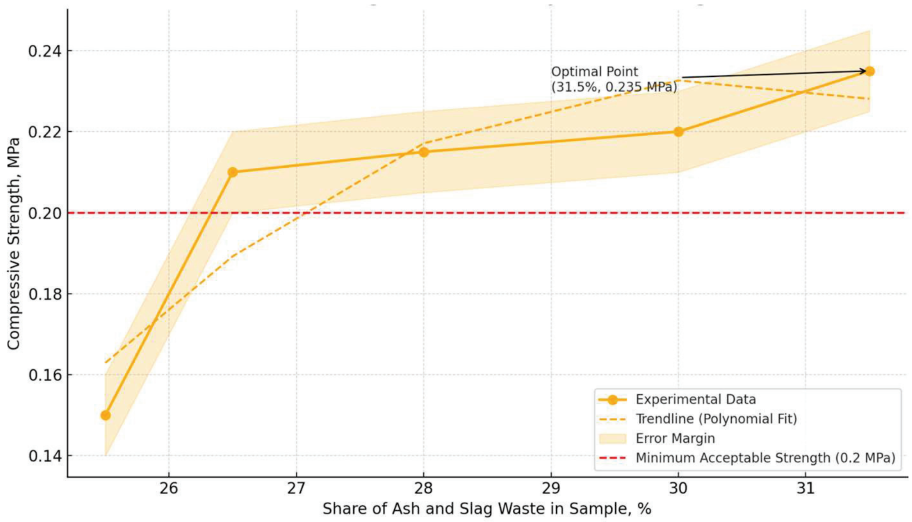


Figure 8. Effect of the amount of ash and slag mixture on the compressive strength of aerated concrete.

Figure 8 illustrates the effect of increasing the ash-and-slag mixture content from 25.5% to 31.5% by weight on the compressive strength of NAAC. The compressive strength improves significantly, rising from 0.15 MPa to 0.235 MPa. The polynomial trendline highlights a consistent upward trend, reflecting the microstructural enhancements observed in Figures 5 and 6, such as improved pore distribution and matrix densification. The inclusion of ash-and-slag additives enhances the mechanical properties of NAAC. It supports environmental sustainability by reducing the harmful impact of industrial waste disposal on soil and water–air environments.

Additionally, the annotated optimal point (31.5%, 0.235 MPa) demonstrates the highest observed strength in the study, while the shaded error margin represents potential variability in results. Including a threshold line at 0.2 MPa emphasizes the material's suitability for applications requiring minimum strength criteria. However, the variability in ash-and-slag waste composition remains a challenge, highlighting the necessity for innovative predictive methodologies to accurately forecast the properties of aerated concrete and ensure consistency in large-scale production. The ongoing research aims to develop an innovative technique to pre-predict the composition of aerated concrete with high accuracy. To activate this technique, it is determined that a minimum amount of data needs to be collected, consisting of 10,000 images of aerated concrete. These images are analyzed using computer vision and deep learning techniques, providing a training sample with sufficient variability to train the neural network and identify complex patterns in the material structure. The selection of 10,000 images is based on established practices in machine learning and image analysis, which suggests that this range provides a robust dataset for training deep learning models to achieve reliable and accurate predictions. Advanced machine learning techniques, including the Mask R-CNN neural network architecture, have contributed to significant progress in predicting the microstructural features of aerated concrete. This advancement plays a key role in manufacturing processes, opening opportunities to assess the quality of the finished product and account for possible changes in material composition during the manufacturing phase. A schematic representation of the aerated concrete composition prediction process is shown in Figure 9. To visualise the process of predicting the composition of aerated concrete, a schematic diagram was developed based on the analysis of the collected dataset using the Mask R-CNN neural network. The images accurately identify different structural elements in the material, including different types of pores and inclusions. Once the model training and validation process is complete, the study moves to the prediction phase where the model determines the microstructural composition of aerated concrete. This allows us not only to assess the quality of the material, but also to identify the features of the composition that affect its characteristics. The obtained data can be used for further improvement of the production process and for adaptation of the material formulation to the requirements to its operational properties. The final assessment of product quality can contribute to improving both the products and their creation processes.

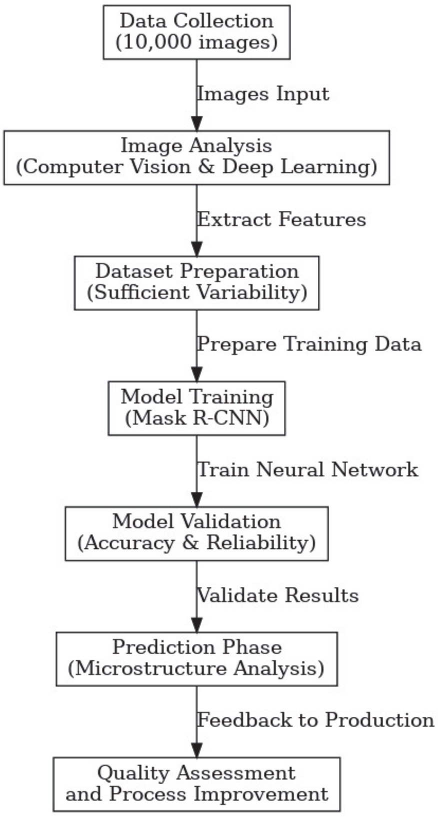


Figure 9. Prediction process for aerated concrete composition using machine learning.

Figure 9 illustrates a schematic representation of the prediction model for the composition of aerated concrete using the Mask R-CNN neural network architecture. It is important to note that this model is currently a conceptual framework and has not yet been fully validated with experimental data. The model's primary objective is to predict the microstructural characteristics of aerated concrete based on a comprehensive dataset of images and physical properties.

The preliminary results from the initial training of the neural network are promising, indicating the potential for accurately identifying different structural elements within the material. However, further validation and refinement of the model is necessary to ensure its reliability and accuracy. We plan to conduct extensive experimental validation of this prediction model and aim to present the detailed results and findings in a subsequent publication. This future study will focus on the model's performance metrics, including prediction accuracy, training and validation processes, and the use of confusion matrices to assess the model's effectiveness in real-world applications.

4. Discussion

This study investigates the incorporation of ASW into NAAC, offering significant dual benefits: effective utilization of industrial waste and enhancement of material performance. The results highlight notable improvements in the physical, mechanical, and microstructural properties of NAAC when ASW content is optimized, supporting its potential for widespread application in sustainable construction.

The compressive strength of NAAC increased from 1.45 MPa to 2.35 MPa as the ASW content rose from 25.5% to 31.5%. This improvement is attributed to the densification and homogenization of the material matrix, as confirmed by SEM and XRD analyses (Figures 5 and 6). The uniform distribution of pores at higher ASW content enhances mechanical stability and thermal insulation, crucial for structural and energy efficiency in construction. This improvement positions NAAC as a superior alternative to traditional autoclaved aerated concrete, offering competitive performance at lower production costs.

The utilization of ASW addresses pressing waste management challenges while reducing the environmental footprint of construction materials. The chemical composition of ASW—predominantly oxides of silicon (51.27%) and aluminum (22.49%)—makes it an ideal additive for NAAC production. Integrating ASW into concrete reduces reliance on natural resources, leading to cost savings. Furthermore, the non-autoclaved production process eliminates the need for high-pressure autoclaves, resulting in lower energy consumption and enabling small-scale, localized production facilities. This makes NAAC particularly suitable for regions with limited industrial infrastructure, enhancing its global applicability.

Integrating neural networks, specifically the Mask R-CNN architecture, significantly advances NAAC research. By analyzing a dataset of over 10,000 microstructural images, the neural network accurately predicts pore distribution and structural characteristics. This capability enhances quality control, enabling manufacturers to fine-tune material compositions to meet specific performance criteria. Additionally, predictive modeling provides valuable insights for optimizing production processes, potentially reducing variability in ASW composition caused by coal quality and combustion conditions.

Despite these promising findings, the study identifies several challenges. Variability in ASW composition remains a critical issue, necessitating the development of robust predictive tools to ensure consistency in material properties. Moreover, while laboratory-scale experiments provide compelling evidence of NAAC's potential, large-scale industrial trials are essential to validate the feasibility of these methods in real-world applications. Including stress–strain analyses and further exploration of ASW's interaction with other components could provide a deeper understanding of its impact on material performance.

The successful integration of ASW into NAAC aligns with global sustainability goals by mitigating waste disposal issues and conserving natural resources. Reducing greenhouse gas emissions and diverting ASW from landfills contribute substantially to environmental stewardship. Moreover, the potential to replace traditional raw materials with ASW offers a scalable and cost-effective pathway to sustainable construction practices worldwide, positioning NAAC as a key material in the transition toward a circular economy.

5. Conclusions

This study confirms the feasibility and effectiveness of utilizing ASW in producing NAAC, offering a sustainable solution for the construction industry. The incorporation of ASW at an optimal content of 31.5% resulted in a compressive strength of 2.35 MPa, significantly enhancing material performance and demonstrating its suitability for environmentally friendly and durable construction applications.

The use of ASW addresses critical challenges, including industrial waste management and environmental impact reduction, while highlighting the economic advantages of the non-autoclaved production method due to its lower energy and material requirements. A particularly intriguing aspect of this study is the application of machine learning technologies, such as the Mask R-CNN neural network, which has provided valuable tools for predicting microstructural characteristics and optimizing material composition.

Despite these promising findings, challenges such as the variability in ASW composition and the need for large-scale industrial validation remain. This underscores the ongoing need for future research and development in this field. The focus should be on refining these technologies and adapting methods to various ASW sources, paving the way for broader application of NAAC in sustainable construction.

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sustainability

Review

Towards Resilient Peatlands: Integrating Ecosystem-Based Strategies, Policy Frameworks, and Management Approaches for Sustainable Transformation

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Abstract: This paper examines the critical importance of peatlands in climate regulation, biodiversity conservation, and the provision of essential ecosystem services, emphasizing the urgent need for their preservation and restoration. Although peatlands cover just 3% of global land, they store 30% of the world's terrestrial carbon, making them vital for mitigating climate change. However, activities such as agriculture, forestry, and peat extraction have caused significant degradation, compromising their ecological integrity and climate functions. This review makes a unique contribution by applying a systems thinking approach to synthesize the interconnected technical, environmental, and socioeconomic dimensions of peatland management, an often underrepresented perspective in existing literature. By offering a holistic and integrative analysis, it identifies key leverage points for effective and sustainable conservation and restoration strategies. This paper also explores the European Union's policy response, including the EU Restoration Law and sustainability initiatives aimed at peatland recovery. It highlights the shift from peat use in energy production to its application in horticulture, reflecting growing demand for sustainable alternatives and eco-friendly restoration practices across Europe. Furthermore, this review addresses the environmental consequences of peat extraction, such as increased greenhouse gas emissions and biodiversity lossand emphasizes the need for robust EU legislation aligned with climate neutrality and biodiversity enhancement goals. It concludes by advocating for comprehensive research and proactive, policy-driven measures to ensure the long-term protection and sustainable use of these vital ecosystems.

Keywords: peatlands; carbon sequestration and storage; EU Restoration Law; peat sustainable management; peatland restoration; biodiversity conservation

1. Introduction

Peatlands are pivotal in regulating the global climate through their significant carbon storage capacity. As the foremost natural terrestrial carbon stores, they have sequestered vast amounts of carbon from the atmosphere since the last glaciation period [1]. However, their degradation due to human activities, such as drainage, peat extraction, and land conversion for agriculture and forestry, has led to substantial carbon emissions, biodiversity loss, and environmental disruption [2]. In Europe, nearly 50% of peatlands have been degraded, with emissions from drained peatlands contributing significantly to greenhouse gas (GHG) emissions [3].

The shift in peatland's over-time use reflects both historical dependencies and modern environmental challenges. Traditionally, peat was extracted for energy production, but its primary use has shifted toward horticulture, where it serves as a growing medium [4]. Peat is generally considered a non-renewable resource due to its slow regeneration rate, though the Intergovernmental Panel on Climate Change (IPCC) categorizes it in a unique category between fossil and renewable resources. While peat extraction accounts for only 0.4% of global peatlands, its GHG emissions are disproportionately high due to the release of stored carbon when peatlands are disturbed [5]. The European Union (EU) has increasingly recognized these impacts, leading to significant policy responses such as the EU Restoration Law, which sets binding targets for peatland restoration in alignment with broader objectives under the European Green Deal and climate neutrality commitments. Yet, despite growing awareness and policy development, peatland management continues to face critical challenges. These include the limited effectiveness of restoration techniques, conflicting land-use priorities, and a lack of integrated data on peat extraction and long-term recovery.

This review arises from the need to overcome these enduring gaps by applying a comprehensive, cross-disciplinary approach. Current approaches to peatland conservation often operate in silos, addressing ecological, technical, or socioeconomic aspects in isolation. In contrast, this paper employs a systems thinking approach, a conceptual framework that emphasizes the dynamic interconnections between ecological systems, policy frameworks, economic drivers, and social contexts. By applying this approach, this review seeks to unpack the complexity of peatland degradation and restoration and to identify strategic leverage points for more sustainable, evidence-based decision-making.

Specifically, this review examines the ecological significance of peatlands, the extent and drivers of their degradation, and the evolving landscape of restoration policies and practices within the EU. Through the systems thinking lens, it evaluates the interdependencies among technical solutions, environmental goals, and socioeconomic trade-offs, offering a comprehensive framework for advancing sustainable peatland management in Europe.

2. Peatland Ecology, Distribution, and Degradation

2.1. Peatland Formation and Types

Peat is a substance formed through the accumulation of dead organic matter, primarily consisting of plant fragments. Unlike sediments moved by water, ice, or wind, peats are unique in that they form in stationary conditions in peatlands. These waterlogged areas impede the decomposition of organic materials, which allow for the accumulation of peat. The process of peat formation is gradual and occurs in environments where the accumulation of organic matter exceeds the rate of decomposition, often due to poor drainage.

Peat varies in composition depending on the geographical region. In arctic, subarctic, and boreal regions, moss peat predominates; in temperate areas, reed, sedge, and forest peat are more common; and in the humid tropics, mangrove and swamp forest peat are found [6]. Peatlands themselves are ecosystems characterized by the accumulation of decomposed organic material. These ecosystems are shaped by a combination of hydrology, soil chemistry, and vegetation, which, together, govern the peat-forming processes.

Peatlands are primarily classified into two types: fens and bogs. Fens are minerotrophic, receiving water from mineral-rich sources; whereas bogs are ombrotrophic, primarily receiving water from precipitation. Bogs are typically more acidic and are dominated by peat mosses, while rich fens are less acidic and often support a more diverse array of plants.

True mosses are usually the most abundant component of undecomposed peat in rich fens [7].

2.2. Peatland Distribution Degradation in Europe

Europe holds a uniquely pivotal role in the global context of peatland conservation. Although covering a relatively small portion of the Earth's land surface, European peatlands are among the most degraded worldwide, with nearly 50% affected by human activities. Yet, the region also leads global restoration efforts, with forward-looking policies such as the EU Restoration Law and the European Green Deal setting ambitious targets for ecological recovery. Europe's peatlands are ecologically diverse, encompassing bogs, fens, and mires across different climate zones, and are critical not only for carbon sequestration but also for water regulation and biodiversity. This dual status as both a major contributor to peatland degradation and a leader in innovative policy response makes Europe's peatland landscape exceptionally significant on the global stage.

Globally, peatlands cover approximately 4.23 million km^2, which represents about 2.84% of the Earth's land surface [8]. Although they occupy a small fraction of the Earth's land area, peatlands are crucial in the global carbon cycle, acting as significant carbon sinks. However, around 12% of these peatlands no longer contribute to peat formation, resulting in considerable carbon loss. The rate of peatland degradation is particularly high in Europe, where nearly 50% of peatlands have been affected by human activities [3].

Peatland degradation is a significant environmental issue as it leads to increased carbon emissions. In certain European countries, the degradation is severe, with 91% to 100% of peatlands affected by activities like agriculture, peat extraction, and forestry. However, there are notable geographical differences. In some regions, less than 20% of peatlands are degraded, demonstrating that successful management practices can make a significant difference in peatland conservation [3].

In central Europe, peatland drainage poses a major environmental challenge, contributing to nearly 25% of the EU agricultural GHG emissions despite representing just 3% of the agricultural land area. This activity significantly affects water quality, drinking water supplies, and biodiversity [9]. Annually, peatland degradation leads to the production of around 2000 Mt CO_2eq of GHGs, or 4% of global anthropogenic emissions [10]. The agricultural sector has been one of the major contributors to peatland degradation, with countries like Hungary, Greece, the Netherlands, Germany, and Poland being the most active in utilizing peatlands for agricultural purposes. Conversely, countries such as Belarus, Lithuania, Ukraine, and Ireland have not been as active in converting peatlands into agricultural lands. Finland, Sweden, and the UK have the lowest percentages of peatland use for agriculture, indicating varied management approaches across Europe [9].

Central European peatlands have been heavily impacted by drainage, tillage, and fertilization, leading to peat shrinkage and loss of organic matter. Forestry is the second-largest land-use activity in the European peatlands, particularly in the Nordic and Baltic states, which have large areas of peat bogs and fens. Fens are less acidic than bogs and support a more diverse plant community, including graminoids, brown mosses, conifers, and deciduous trees. The term mire is often used to refer to both acid bogs and alkaline fens, ecosystems where peat accumulation is still ongoing. These ecosystems are crucial not only for carbon sequestration but also for regulating greenhouse gas fluxes and supporting biodiversity [11,12].

In Latvia, peatlands cover a significant portion of the country, with 9232 km^2 of peatland, of which 3165 km^2 are classified as mire areas. Of the total peatland area, 6066 km^2 is degraded, and only 10 km^2 has been restored [13]. The total peat deposit in

Latvia is estimated at 1.7 billion tons, with 145.7 million tons of peat having been harvested by the start of 2019 [14].

Latvia's peatlands are categorized as intact, degraded, and restored, each reflecting the varying ecological integrity of the peatlands. Intact peatlands are still functional and preserve their ecological benefits, such as carbon sequestration and biodiversity conservation. However, a significant portion has been degraded due to human activities like agriculture, forestry, and peat extraction. The restored areas are still limited compared to degraded ones but represent ongoing efforts toward ecological rehabilitation.

Historically, peat has played an important role in Latvia's economy, used for heating, soil improvement, and as bedding material [15]. Today, the majority of peat extraction is aimed at industrial uses, particularly in horticulture. While peat continues to be an important resource for agriculture, horticulture, and energy production, its intensive exploitation is a leading cause of peatland degradation. Approximately 7.7% of Latvia's agricultural land and a large portion of its forests are located on drained peatlands, which signifies significant human intervention [15].

The degradation of peatlands, especially in Europe, presents significant challenges, but it also provides opportunities for improving peatland management and implementing restoration strategies. The situation in Latvia highlights the difficulties of balancing peatland use for economic activities like agriculture and horticulture with the need for conservation and restoration efforts. Effective management practices, informed by scientific research, policy frameworks, and socioeconomic considerations, will be essential for achieving the restoration and conservation goals needed to maintain the ecological functions of peatlands.

3. Policy Framework for Peatland Management in Europe

Peatlands are a key focus of European conservation efforts due to their environmental significance. In response, the European Union has developed legislative frameworks and restoration targets to protect and restore the peatland ecosystems.

3.1. EU Policy Initiatives for Peatland Restoration

In 2022, the European Parliament introduced the Nature Restoration Law, establishing legally binding restoration targets across various ecosystems, including peatlands, forests, grasslands, rivers, and coastal areas [16]. This law aligns with the EU's broader environmental and climate goals, including the Biodiversity Strategy for 2030, which calls for restoring at least 30% of degraded habitats by 2030. The Climate Change Adaptation Communication of 2021 further emphasizes the need for cost-effective, nature-based solutions, such as the following [17]:

- Protecting and restoring wetlands and peatlands;
- Enhancing ecosystem resilience;
- Developing green infrastructure;
- Sustainably managing farmlands and forests to mitigate emissions.

The EU has set ambitious targets to reduce net greenhouse gas (GHG) emissions by at least 55% by 2030, with the land-use sector (LULUCF) playing a critical role in achieving this goal [18]. Several legislative instruments directly or indirectly influence peatland conservation, restoration, and management, including, Natura 2000, the Environmental Impact Assessment Directive, Cross-compliance and Greening under the Common Agriculture Policy, the Water Framework Directive, the EU Flood Directive, Climate and Land Use Policies, Renewable Energy Policies, and initiatives for peat in horticulture and specific incentive schemes, alongside the LIFE financial instrument.

The Nature Restoration Law sets targets for peatland restoration to mitigate climate change and biodiversity loss, aiming to restore 30% of drained peatlands by 2030, 50% by 2040, and 70% by 2050, with significant portions to be rewetted. These efforts align with the EU's broader ecosystem restoration goals and its international environmental [19–21]. Despite the EU's commitment to peatland restoration, the implementation of these targets has encountered political resistance and stakeholder concerns, particularly from the agricultural sector.

One of the primary challenges is the impact of rewetting on agricultural land use, as many drained peatlands are currently used for farming. Rewetting these areas could reduce land productivity, affecting food production and rural economies, and leading to opposition from farmers and industry stakeholders. Additionally, the high economic costs of restoration pose a significant barrier, as restoring degraded peatlands requires substantial financial investment, and some member states lack sufficient funding to support large-scale efforts. Moreover, conflicts with landowners have emerged, as restrictions on drained peatlands limit their use, raising concerns over property rights and compensation. In response, the EU has introduced financial support mechanisms, including the LIFE program, Common Agricultural Policy (CAP) Eco-Schemes, and Just Transition Funds, to assist member states in implementing restoration initiatives and addressing economic challenges [22,23].

3.2. National and Regional Policy Approaches

While the European Union has set ambitious goals for peatland restoration, the implementation of these policies varies across member states. Each country faces unique environmental, economic, and political challenges, influencing the way restoration efforts are designed and executed. Some nations have embraced large-scale peatland recovery projects, while others struggle with land-use conflicts and financial limitations.

In Sweden, the target is set to rewet at least 50% of the country's peatlands by 2030, focusing on 100,000 hectares of forested peatlands and 10,000 hectares of agricultural land. Norway, on the other hand, has concentrated its efforts on protecting nature reserves and restoring degraded bogs, aiming to rehabilitate 15% of the country's damaged ecosystems by 2025. Between 2015 and 2021, Norwegian restoration programs successfully restored 105 bogs by blocking drainage ditches and re-establishing natural hydrology [10].

The United Kingdom has also taken an active role in peatland conservation. Through the England Peat Action Plan, the country aims to restore 280,000 hectares of peatlands by 2050 as part of its broader Net Zero strategy. Meanwhile, Scotland has committed £250 million to rewet 250,000 hectares by 2032, recognizing the crucial role of peatlands in carbon storage and biodiversity conservation.

Germany, where drained peatlands contribute significantly to national CO_2 emissions, has pledged to cut these emissions by 5 million tons by 2030. Similarly, Denmark has made peatland restoration a priority within its agriculture transition agreement, requiring the rewetting of 58% of organic-rich soils by the end of the decade.

In the Baltic region, peatland restoration efforts are also gaining traction. Lithuania has committed to restoring 8000 hectares of degraded peatlands by 2026, focusing on reducing emissions and improving wetland biodiversity. Neighboring Latvia has set a target to rehabilitate 26,000 hectares of former peat extraction sites by 2030, balancing environmental recovery with the economic realities of peat production [15].

Despite these commitments, many countries face significant hurdles in meeting their restoration goals. Funding limitations, land-use conflicts, and stakeholder resistance often slow down progress. Ultimately, while national policies are moving in the right direction, more effort is needed to overcome financial and political barriers. Collaboration between governments, scientists, and local stakeholders will be essential to ensuring long-term peatland recovery and achieving the EU's broader climate and biodiversity objectives.

3.3. Regulations on Peat Extraction

Beyond restoration efforts, many European countries are also adopting stricter regulations on peat extraction, particularly in the energy and horticulture sectors. As scientific evidence mounts on the high carbon footprint of peat use, governments are under pressure to phase out peat harvesting and transition to more sustainable alternatives.

The United Kingdom has been a frontrunner in regulating peat use, especially in the horticulture industry. As early as 1995, the UK introduced targets to reduce peat in growing media, aiming for a 40% reduction by 2005 and 90% by 2010. More recently, the government has taken a stronger stance, announcing a ban on retail peat sales starting in 2024, with a full phase-out for professional growers by 2028 [24].

Germany, which has historically been one of the largest consumers of peat for horticulture, has also committed to phasing out peat extraction. Under its National peatland Strategy, adopted in October 2022, the country plans to completely end peat extraction by 2040 and gradually phase out its use in horticulture between 2027 and 2031 [25].

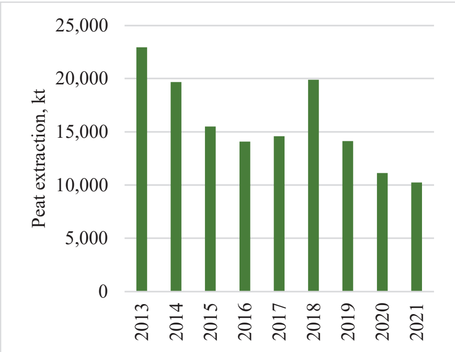
However, the transition away from peat is not without challenges. Many industries, particularly in horticulture, remain heavily reliant on peat, and finding viable alternatives has proven difficult. Materials such as coir, wood chips, and composted bark are increasingly being used as substitutes, but supply shortages, higher costs, and quality inconsistencies have made large-scale adoption difficult. The shift away from peat is also creating economic disruptions in regions where peat extraction has historically been a major employer, leading some governments to introduce compensation and transition programs for affected workers.

Another concern is the increasing reliance on peat imports from non-EU countries, as local extraction is phased out. This raises questions about sustainability and carbon leakage, as imported peat may still contribute to emissions and biodiversity loss in other parts of the world. Some experts argue that stronger sustainability certifications and international trade agreements will be necessary to ensure that the EU's shift away from peat does not simply shift environmental harm elsewhere.

4. Extraction, Trade, and Application of Peat in the Horticulture and Energy Sector

4.1. Extraction and Market Dynamics of Peat

To implement the peatland restoration measures set by the EU, the understanding of the current scale of peat extraction and use is essential to assess the potential impact on peat-based industries and the overall socioeconomic situation. Around 80% of peat extraction worldwide takes place in Europe [4]. According to the Eurostat data, peat is produced in 11 EU countries—Germany, Estonia, Finland, Ireland, Latvia, Lithuania, Poland, Sweden, Denmark, Spain, and Romania. The total amount of extracted peat in the EU27 in the period from 2013 to 2021 is shown in Figure 1a. In 2021, total peat production in the EU amounted to 10.2 million tons. Nevertheless, the European peat market is showing a downward trend by the targeted regulatory strategy to reduce peat production and consumption in the EU. During the last decade from 2010 to 2019, the average total amount of extracted peat in EU27 was 17.4 million tons per year. A negative trend in terms of peat production is evident also worldwide. Peat extraction across Europe is decreasing following concerns over climate change and biodiversity loss announced by the EU Council in 2018. An increasing number of EU policies include the management of drained peatlands as an essential solution for the reduction of GHG emissions and climate change mitigation. New policies are moving towards responsible use of peat resources and strongly discourage peat extraction. All the recent announcements have affected the European peat market considerably. The leading peat producer in the EU in 2021 was Germany (3228 kt) followed distantly by Finland (1582 kt), Latvia (1248 kt), Poland (1238 kt), and Estonia (906 kt) (Figure 1b).



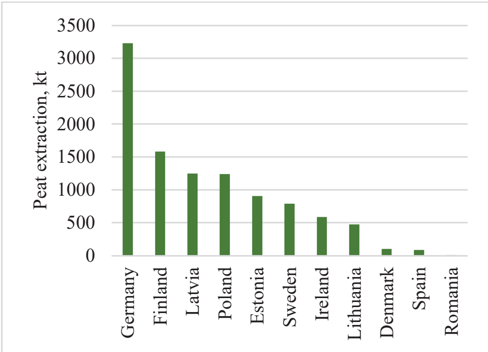


Figure 1. (**a**) Total peat extraction and (**b**) peat-extracting countries in 2021 in the EU27.

Peat extraction across Europe is decreasing following concerns over climate change and biodiversity loss announced by the EU Council in 2018. An increasing number of EU policies include the management of drained peatlands as an essential solution for the reduction of GHG emissions and climate change mitigation. New policies are moving towards responsible use of peat resources and strongly discourage peat extraction. All the recent announcements have affected the European peat market considerably.

Although Finland has been the major producer of peat in Europe for a long time, significant changes in the top producers of peat in Europe can be observed in the last couple of years (Figure 2). Rearrangement of leaders took place in 2020 following the decision to cut out peat from energy use in Finland resulting in a considerable reduction in peat extraction volume. A more than fourfold decrease in peat extraction was observed in Finland in 2021 compared to 2018. An even greater reduction of peat extraction took place in Ireland decreasing by more than six times compared to the 2018 volume following the decision to start phasing out the harvesting of peat to produce heat and electricity by 2030. Peat production in Germany has been relatively constant with moderate growth in the past years; however, Germany came out on the top in 2020 due to the decrease in peat extraction in Finland and Ireland.

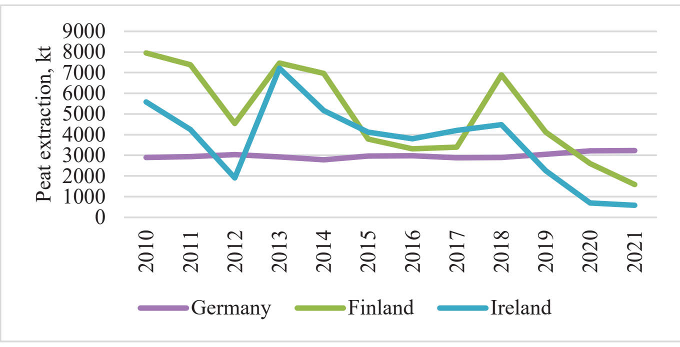
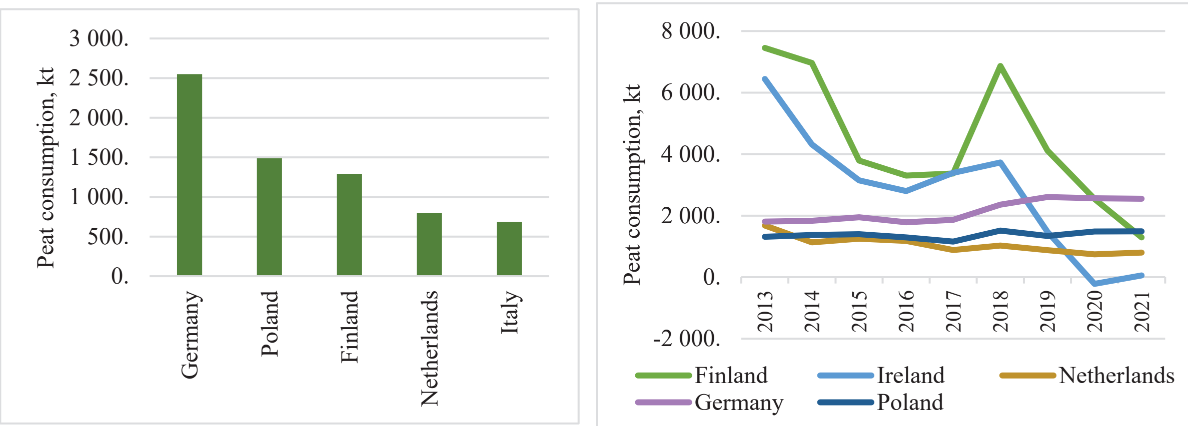


Figure 2. Peat production of top peat-producing EU countries in the period from 2010 to 2021.

Total consumption of peat in the EU in 2021 reached 8365 kt. The largest consumer of peat by far was Germany, with a total consumption of 2549 kt of peat, accounting for 30% of the total peat consumed in the EU (Figure 3a). Poland and Finland shared second and third place, respectively, with 17.8 and 15% of the total consumption.



(**a**) (**b**)

Figure 3. (**a**) Domestic consumption of peat in 2021 and (**b**) dynamics of peat consumption of major consumers of peat in the EU.

Similar to production, the domestic consumption of peat in the EU has undergone major changes in the last couple of years (Figure 3b). The greatest changes in consumption can be seen in Finland and Ireland due to the cut of peat used for energy. In other European countries, peat consumption has been showing a relatively flat trend with a slight increase in consumption in some countries (Germany, Poland) but a decrease in others (The Netherlands). Peat exports have shown an upward trend in the EU in the last decade (Figure 4). The top five peat exporting countries in 2021 were Latvia, Germany, the Netherlands, Estonia, and Lithuania (Figure 6). The leading country, Latvia, exported 2235 thousand tons of peat, followed by Germany with 1726 and the Netherlands with nearly 1500 thousand tons.

Figure 4. Total exports and imports of peat in the EU.

Similar to exports, imports of peat have experienced growth in the last decade, although the volume of imported peat is significantly smaller (Figure 4). The largest importer of peat by far is the Netherlands, reaching 2279 thousand tons in 2021, more than double the share of the second-largest importer, Germany (1048 kt, Figure 5). Italy, France, and Belgium imported 697, 630, and 571 thousand tons of peat, respectively.

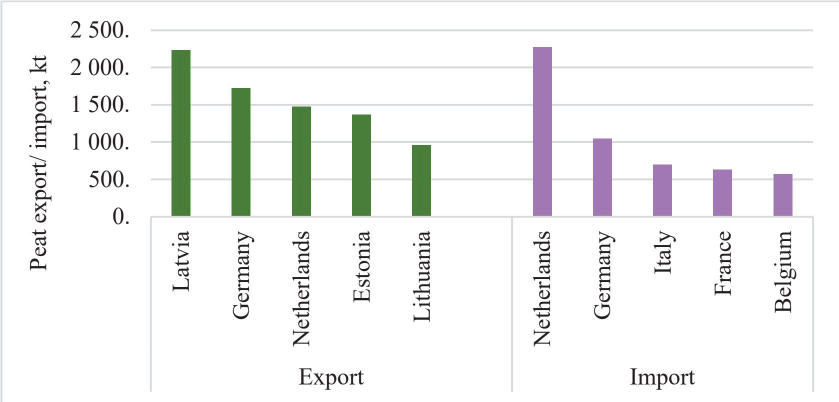


Figure 5. Top five peat exporting and importing countries in the EU in 2021.

Imports of peat have stayed relatively constant in recent years with, no change in the top importing countries (Figure 6). An increase in peat imports in recent years can be observed in Italy. According to the IndexBox [26] the average export price of peat in the EU was USD 126 per ton in 2021, showing an increase of 5.7% compared to the previous year.

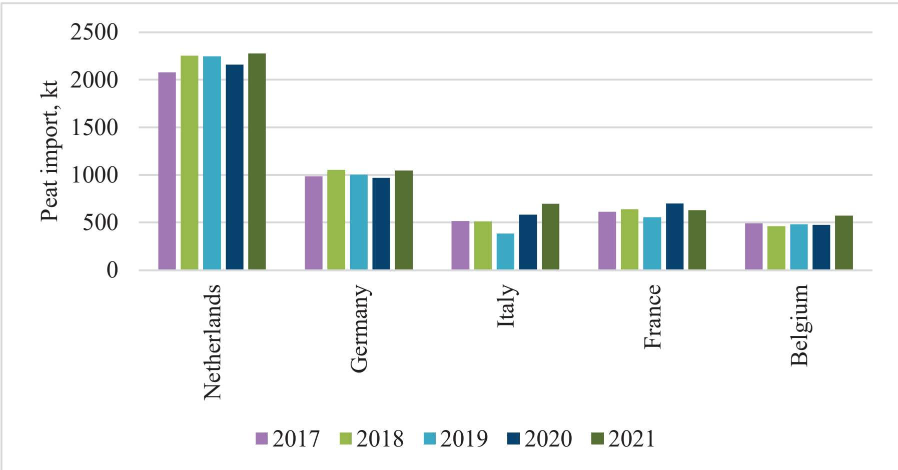


Figure 6. Dynamics of the leading peat importers during the past five years.

The import price amounted to USD 119 per ton, growing by 9.2% compared to the previous year. According to TrendEconomy [10], the total value of peat (2703) exports from the EU reached USD 447 million in 2022, going up by 0.558% compared to 2021. The value of imports of peat (2703) to the EU was USD 52 million in 2022. Sales of peat to the EU went up by 7.88% compared to 2021.

According to TrendEconomy [27], the largest amount (in terms of value) of peat from the EU was exported to China (21%), the United Kingdom (7.02%), the USA (5.15%), Saudi Arabia (4.48%), and Switzerland (4.12%); whereas the largest exporters of peat (in terms of value) into the EU were Belarus (59%), Russia (17.1%), the United Kingdom (13.2%), Ukraine (5.26%), and Bosnia and Herzegovina (1.75%). A further decrease in peat extraction is expected in the near future following decisions to phase out the peat used for energy as well as the replacement of peat in growing media mixes.

Peat extraction is intrinsically linked to peatland drainage as the removal of peat requires lowering the water table to access the material, effectively halting peat accumulation and transforming carbon sinks into carbon sources [28]. This practice significantly contributes to greenhouse gas emissions, biodiversity loss, and long-term land degradation [29]. Despite declining extraction volumes in recent years due to policy shifts, the ecological impact of historically drained and currently exploited peatlands remains substantial. Rewetting these drained sites has emerged as a critical restoration strategy to reverse environmental damage and re-establish peatland functions [30]. However, rewetting efforts in former extraction areas often face practical challenges, including altered hydrology, residual soil compaction, and conflicting land-use interests [31]. While some countries, like Ireland and Germany, have initiated large-scale rehabilitation programs for post-extraction peatlands, such measures are have not yet been uniformly adopted across Europe. Integrating rewetting into peatland management plans, particularly in areas of ongoing horticultural extraction, is essential for achieving long-term climate and biodiversity goals outlined in EU environmental policy [32].

4.2. Peat Use in Horticulture and Energy Production

Since the 1950s, peat has become the main constituent of horticultural growing media [4] and is widely used in the pot plant industry, as a soil conditioner, and an organic fertilizer [33]. Peat is one of the most important growing media constituents due to its low cost, high availability, and suitable physiochemical properties. As a soil conditioner, pet can improve soil chemical properties and structure (e.g., pH, level of nutrients, oxygen supply) as well as water retention and drainage capability [34].

In peat-rich countries such as Finland, Germany, Ireland, Sweden, and the UK, domestic peat resources provide horticultural companies with peat for their needs. On the other hand, countries such as the Netherlands, Belgium, France, Italy, and Spain depend on imports of peat or peat-based growing media to sustain their horticultural sector [35]. Europe, especially the Baltic States, is by far the main supplier of peat and peat-based growing media in the world [36]. Peat for horticultural purposes is intensively traded in Europe. Most of the end consumption of peat in the form of growing media in the horticultural production sector or by private gardeners takes place in Western Europe, with the Netherlands and Germany being the main consumers [36]. On the other hand, peat production is taking place mainly in the Central, Northern, and Baltic states. Exports of peat to other EU and non-EU countries represent 85% of the extracted volume. In comparison, imports from outside Europe are very limited [36]. The trade of horticultural products within Europe is also important: exports of horticultural products within Europe represent around 50% of the European horticultural production in value [36].

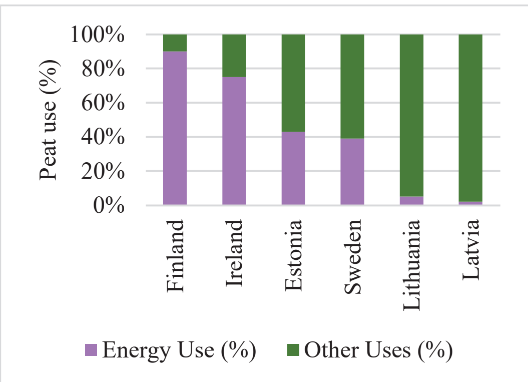
Peat is the predominant growing medium constituent used in Europe, accounting for 75% of the volume [37–39]. The latest data on growing media production in Europe were provided by Schmilewski [38]. This study reported that the total growing media production in Europe was around 35 million m^3 in 2013; no more-recent data on the production of growing media could be found. These data are in accordance with another survey by Altmann [37]. Around 20 million m^3 are used in professional horticulture, whereas 15 million m^3 are in the hobby market [38].

Germany leads as the primary producer of growing media within the European Union, with the Netherlands and Italy following in production capacity [38]. The dependence on imported peat for growing media production is notable in these countries, highlighting the international dynamics of peat trade. Germany and the Netherlands not only dominate in production but also consumption of these growing mediums [36].

Peat's contribution to growing media mixtures shows significant variation across Europe. For instance, Denmark and Ireland see peat making up 87% of their growing media, with even higher percentages in Finland (88%), Latvia (92%), and astonishingly, nearly all (99%) in Estonia and Lithuania. This contrasts sharply with Italy and the United Kingdom, where peat constitutes a smaller fraction of the media composition, 64% and 54%, respectively [38]. The Netherlands plays a pivotal role in the European growing media market, despite having ceased domestic peat extraction [36]. Its substantial horticultural sector, which boasts a turnover of 6 billion euros and leads globally to cut flower production, demands significant volumes of growing media [40]. The country's reliance on peat imports underlines the critical need for these materials in supporting its horticulture industry, which is also a significant producer of container plants. The Dutch horticulture sector's reliance on a steady supply of growing media underscores the strategic importance of peat and its substitutes in maintaining the country's leading position in global horticulture [41].

The use of peat for energy production has a long history in Europe, especially in countries with large peat resources [37,42,43]. Until very recently, in several Nordic countries and Ireland, and to some extent in the Baltic states, peat provided an important source of heat and power [41,44,45]. Although there are several advantages to using peat for energy production, such as energy security, diversification, and decentralization, there are rising concerns about the environmental impact of burning peat. Emissions released from peat combustion are equal to those of fossil fuels. The EU's target is to phase out peat from energy use across the EU by 2050 to ensure the set climate and energy targets. Therefore, in recent years, substantial changes have taken place in the energy peat sector. Following the EU legislation, governments are promoting the generation of energy through renewable sources. This has increased from alternative energy sources such as solar, wind, and biogas and a substantial decrease in the use of peat.

In 2019, the share of peat production for energy use was highest in Finland, reaching 90%, and in Ireland, reaching around 75% of the total peat production (Figure 7a). Estonia and Sweden use around 40% of peat for energy production; however, peat extraction is almost entirely for agricultural use in Lithuania and Latvia, and peat share in total energy production is negligible. The total extraction area for fuel peat in the EU was recently found to be 1750 km^2 (0.34% of the total peatland area). Most of the peat for energy is consumed where it is extracted; therefore, the international trade of energy peat almost does not exist [4].



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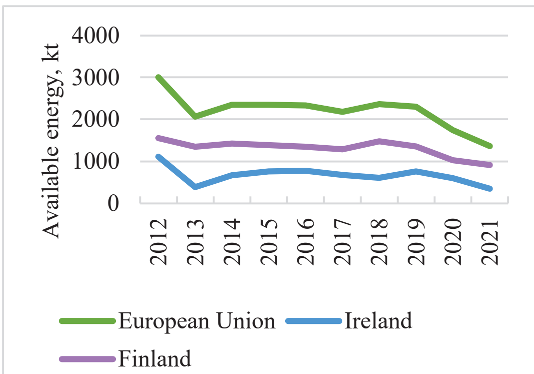

(**b**)

Figure 7. (**a**) Share of peat for energy uses in 2019 (JRC, 2021). (**b**) The use of peat for energy production in the EU and two major energy peat countries.

The total production of fuel peat in energy peat EU countries (FI, IE, EE, SE, LT, LV, and RO) was 1370 ktoe in 2021, resulting in a total of 16 TWh energy. The largest producers and consumers of energy peat within EU27 are Finland, Ireland, and to a lesser extent, Sweden. The production of energy peat has decreased considerably in the last few years (Figure 7b). A total decrease of 42% can be observed in 2021 compared to 2018. The observed decrease is a result of the governmental policies to significantly reduce the use of peat for energy purposes in the two largest energy peat countries, Finland and Ireland, accounting for 92% of the total energy peat production in the EU, as shown in Figure 7b. In Finland and Ireland, 913 kt and 349 kt of peat were extracted for energy purposes in 2021, respectively.

The decrease in energy peat production in Finland and Ireland in 2021 was 38 and 43%, respectively, compared to the 2018 level. An even larger decrease of 67% can be observed in Sweden in 2021, even if the total amount of energy peat consumed is much smaller. In other European countries, such as Estonia, Lithuania, and Latvia, the use of peat energy has also decreased considerably and is negligible (Figure 8). Romania is the only country where the use of energy peat has increased in recent years; however, the amount is very small.

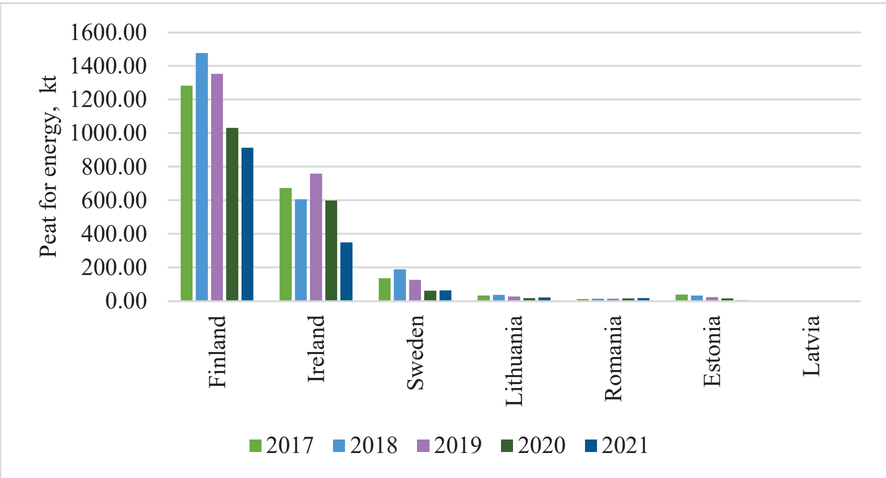

Figure 8. Energy produced from peat in energy peat countries in the EU.

Being the largest energy peat user, Finland generated 16 TWh of energy from peat on average per year from 2012 to 2019. Energy peat was used in 260 boilers in Finland, which produced district heat and heat for industry, as well as electricity for cogeneration [46]. The share of peat in the energy mix in Finland has been steadily declining. Peat use as a fuel is planned to be cut by 50% by 2030 [4], with the phase-out of the industrial use of energy peat to following shortly after [44]. One tool for the implementation of such measures was the increase in energy tax on peat, which almost doubled in 2019 [24]. In recent years, energy from peat combustion has accounted for less than 4% of the total annual energy consumption; however, it is responsible for more than 10% of the country's annual GHG emissions [47]. Energy peat use decreased by 14% in 2021 compared to 2020, contributing 3% to the total energy consumption [47].

Ireland is the second-largest producer and consumer of energy peat in the EU. In 2015, Ireland's Ministry for Energy announced the beginning of the phase-out of the harvesting of peat to produce heat and electricity by 2030. Already in 2020, Ireland withdrew peat from the electricity generation process and transitioned to alternative fuel sources [48]. As a result of the shutdown of two peat-fired power plants, the overall CO_2 emissions from electricity generation fell by 7% [49]. Peat briquette production has been decreasing since the early 1990s. In 2021, 2% of the total Irelands energy was produced from peat [48]. According to Ireland's major peat extraction company, Bord na Móna, 55 ktoe peat briquettes were still produced in 2021 [48]. Peat is still used in the residential sector in Ireland. Both sod peat and peat briquettes are used for heating households [50]. It is expected that the use of peat for energy purposes will continue to decrease in the EU in the coming years due to political strategies adopted by member countries in accordance with the EU's climate neutrality targets.

Overall, market analysis shows a significant decline in energy peat consumption, with ongoing replacement by biomass in energy production. The shift to alternative bioenergy sources at the national level is driven by emission allowances for peat burning, whereas wood biomass is deemed emission-free. In Finland, peat has been replaced by wood biomass, including wood chips, sawdust, forest residues, and bark. This decline is expected to continue. The reduction in peat use, alongside coal withdrawal, affects energy supply security, positioning wood biomass as the primary fuel option [46].

Studies have been focusing on renewable materials from agricultural, industrial, and municipal waste streams [51]. Some of the main alternatives are wood chips or bark, green compost, and coir pith [52–54]. Moreover, the proportion of peat in peat-containing growing media has also decreased. However, phasing out peat in the horticulture field faces some important challenges. Resource availability to produce alternative growing media constituents is one of the major concerns of the growing media industry [36].

Peat-free alternatives like coir, often sourced internationally, face potential supply shortages and disruptions due to global factors. Environmental impacts from shipping and varying production costs of alternative growing media also raise concerns. Despite these issues, the peat remains economically more favorable than its alternatives [55]. Further research on alternative materials to produce growing media is needed, including prices, sustainability, and security assessment, to move towards peat-free growing media.

5. Challenges and Opportunities in Peatland Restoration

Restoring peatlands has emerged as a priority, with the potential to deliver significant environmental, economic, and social benefits. However, the restoration of peatlands is a complex and multifaceted process. It requires balancing the ecological needs of the land with economic considerations, societal impacts, and scientific uncertainties. The strategies for restoration, such as rewetting, revegetation, and after-use management (including land conversion for agricultural or forestry purposes), all come with challenges and opportunities. This chapter explores the key restoration strategies for peatlands, highlighting the most promising opportunities and addressing the major challenges faced in peatland restoration efforts.

5.1. Key Challenges in Peatland Restoration

Despite the clear benefits of peatland restoration, several challenges remain. From scientific uncertainties about emissions fluxes to socioeconomic barriers, restoring peatlands requires overcoming numerous obstacles. The management of the ecosystem, the procedures for monitoring and reporting, the need for an adequate database, and the implementation of policies are potential major obstacles to peatland restoration.

One significant challenge is the monitoring of ecosystem services. These services must be evaluated against baselines to assess restoration progress. However, large-scale restoration efforts often make ground-based measurements impractical, necessitating the development of affordable techniques such as remote sensing technologies that link vegetation growth and greenhouse gas fluxes. Long-term ecosystem function monitoring is costly, and existing methods often lack standardization, complicating comprehensive assessments of restoration effectiveness. Moreover, inaccurate reporting of greenhouse gas emissions, especially from organic soils, remains a significant problem [7,56]. Many nations struggle to report organic soil emissions accurately, leading to uncertainties in national GHG inventories [57]. This reporting gap is particularly critical given the vulnerability of peatlands as carbon sinks. Drainage, extraction, and warming-induced changes in hydrology can accelerate carbon losses from peat soils, undermining their long-term storage function. Without urgent mitigation efforts, such as rewetting, improved monitoring, and policy integration, the balance and resilience of these ecosystems remain at risk. Enhancing the stability of peatland carbon sinks is not only essential for ecosystem integrity but also plays a pivotal role in achieving regional and global climate mitigation targets.

Another critical challenge is policy integration across several sectors. Effective implementation requires coordination amongst multiple stakeholders, including environmental authorities, agriculture, forestry, and water management. While increasing awareness of peatland restoration is a priority, effective implementation remains hindered by the lack of coordination across sectors. Restoration efforts require collaboration between environmental authorities, agriculture, forestry, and water management agencies. Without this coordination, national peatland restoration policies face substantial barriers to success. Additionally, in some regions with significant land-use pressures, such as the Netherlands, restoration opportunities are limited due to dense populations and intensive agriculture, while areas with lower land pressures, such as Central and Eastern Europe, offer greater restoration potential [25,58,59].

Another barrier to successful peatland restoration is policy coordination. Restoration efforts often require the involvement of multiple stakeholders, including environmental authorities, agriculture, forestry, and water management agencies. In some countries, a lack of coordination between these sectors has delayed or hampered restoration projects. This is particularly problematic in regions with intensive agricultural practices, where land use priorities often conflict with the goals of restoration [10].

The key to effective restoration lies in addressing these challenges through coordinated efforts, site-specific approaches, and innovative solutions to balance the ecological benefits with the economic realities of the affected communities.

5.2. Restoration Strategies and Opportunities

Peatland restoration is crucial for addressing pressing environmental challenges such as carbon sequestration, climate change mitigation, and biodiversity preservation. Peatlands store substantial amounts of carbon, which is released into the atmosphere when these ecosystems are damaged, contributing to climate change. Therefore, restoring peatlands not only mitigates carbon emissions but also aids in revitalizing biodiversity and supporting ecosystem services [60].

Restoration strategies generally focus on improving the hydrological conditions of degraded peatlands, with rewetting being one of the most effective methods. Rewetting involves raising the water table to restore natural hydrological conditions, thereby reducing carbon emissions and allowing peatlands to regain their role as carbon sinks. This is especially important for drained peatlands, which are major sources of GHG emissions. However, rewetting requires careful management to prevent CH_4 emissions, which can increase in the short term due to changes in water levels and microbial activity in rewetted soils.

Figure 9 illustrates how carbon dynamics in peatlands depend on the balance between photosynthesis and respiration. The efficiency of carbon capture through photosynthesis is influenced by several factors, including the photosynthetically active radiation (PAR), the vegetation cover (Leaf Area Index, LAI), the length of the growing season, the temperature, and the optimal groundwater levels. Fluctuations in these factors can significantly affect the ability of peatlands to sequester carbon. Additionally, methane (CH_4) and nitrous oxide (N_2O) emissions are linked to water levels, nutrient availability, and the type of vegetation, highlighting the complexity of managing carbon dynamics in peatland ecosystems [60].

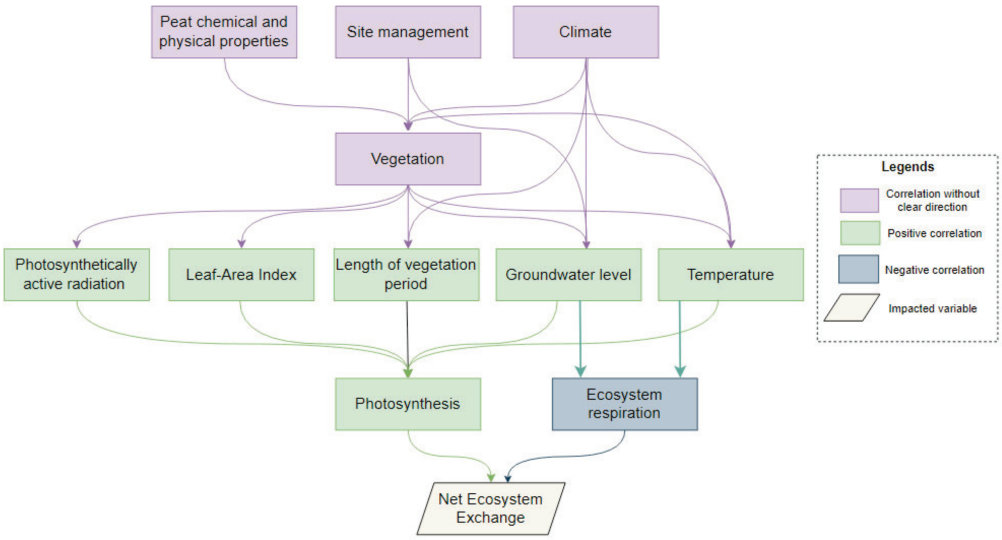

Figure 9. Variables influencing net ecosystem exchange on peatlands readapted from [60].

Restoring peatlands through renaturalization—or rewetting—is a priority in many restoration projects. Rewetting helps to re-establish hydrological conditions, which are vital for carbon sequestration and biodiversity. Ideally, the water table should remain 20–30 cm below the surface year-round to maintain optimal conditions for peatland ecosystems to thrive [61]. Technological interventions, such as drainage blocks, can help retain water in formerly drained peatlands, gradually raising the groundwater levels and restoring natural conditions.

Afforestation is another potential after-use for degraded peatlands. Forestry can sequester carbon and restore biodiversity, but its long-term climate benefits are still uncertain. While tree planting enhances carbon sequestration, there are concerns that the carbon loss from the original peat might not be fully compensated by forest growth, especially when considering the long-term carbon dynamics of the peat itself [62].

Other land uses, such as croplands, blueberry, and cranberry farming or perennial grasslands, offer both economic opportunities and climate change mitigation. However, these activities often generate higher GHG emissions than wetland restoration. In particular, converting drained peatlands to croplands can result in high CO_2 emissions, making it a less viable option for climate mitigation compared to rewetting [63].

Paludiculture—the practice of cultivating wetland plants on rewetted peatlands—has also been recognized as a promising alternative. Plants such as reeds, cattails, and *Sphagnum mosses* can be cultivated in periodically flooded peat soils, offering both biodiversity value and carbon sequestration potential. In addition, paludicultures can provide renewable biomass for energy production, offering an alternative to fossil fuels. This practice helps maintain peatland hydrology, reducing peat oxidation and further enhancing carbon capture [64].

However, emissions from rewetted peatlands remain uncertain, particularly concerning methane (CH_4) and nitrous oxide (N_2O) emissions. While methane emissions may increase for up to 30 years after rewetting, the growth of diverse vegetation can help mitigate these effects. Similarly, nitrous oxide emissions are highly variable and are influenced by factors such as land use and location effects [65,66]. Rewetting is not always suitable for all peatlands, as its effectiveness depends on site-specific conditions. In some cases, rewetting could lead to short-term negative impacts, such as water quality degradation or reduced agricultural viability due to elevated water levels [7,67]. Therefore, careful site assessment is crucial before implementing rewetting.

The sustainable development of European peatlands requires an integrated framework that reconciles ecological restoration with socioeconomic demands. As peat remains a key input in the horticultural and agricultural sectors, particularly as a high-quality substrate, transitioning toward environmentally responsible alternatives is imperative. Approaches such as paludiculture present viable options for productive land use on rewetted peatlands, offering climate mitigation benefits through carbon sequestration while supporting biodiversity and rural economies. Effective peatland management should be grounded in climate-resilient policies, the promotion of peat-free growing media, and support for multifunctional land use that aligns with conservation goals. In this context, the integration of ecological, economic, and policy instruments is essential to ensure that peatland use contributes to the European Union's broader objectives for climate neutrality, biodiversity protection, and sustainable agricultural development [68,69].

5.3. Systems Approach to Peatland Management

The restoration and sustainable management of peatlands require a multifaceted approach, as these ecosystems are shaped by a complex interplay of ecological, socioeconomic, and policy-driven factors. A system-thinking perspective is essential for understanding how different variables interact between peatland degradation, climate change, governance, and socioeconomic factors. The causal loop diagram shown in Figure 10 illustrates the interconnected feedback mechanisms that influence peatland ecosystems, offering a comprehensive perspective on how various environmental, socioeconomic, and policy-related factors interact in shaping the better peatland ecosystem. Two opposing feedback loops drive the fate of peatlands:

1. A reinforcing loop ("R") that accelerates peatland degradation and climate change.
2. A balancing loop ("B") that attempts to counteract these effects through governance, restoration, and sustainable management.

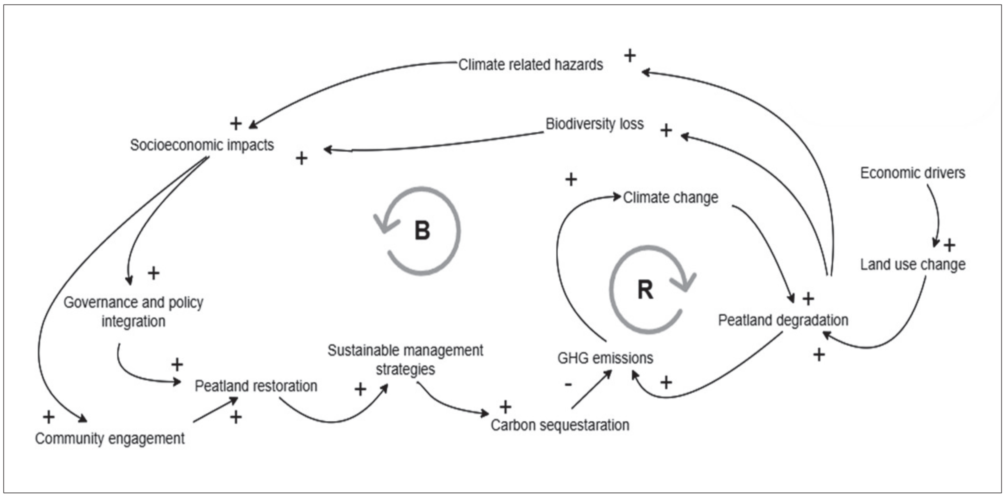

Figure 10. A systems approach to peatland degradation and restoration.

Peatland degradation is primarily driven by economic incentives, leading to extensive land use changes, such as drainage for agriculture, forestry, and peat extraction. These activities set off a reinforcing feedback loop ("R") where degraded peatlands, once strong carbon sinks, become major sources of GHG emissions. As emissions rise, climate change intensifies, triggering more extreme weather events, droughts, and wildfires, which further degrade peatlands. The feedback loop underscores the urgency of intervention as even though peatlands occupy only a small fraction of the earth's surface, they contribute disproportionately to global carbon emissions when degraded.

However, the balancing loop ("B") represents the possibility of breaking free from this pattern through peatland restoration, governance, and community-driven conservation efforts. Peatland restoration plays a dual role: not only does it rebuild ecosystems and biodiversity but it also strengthens carbon sequestration, counteracting emissions. Yet, restoration is only successful when supported by strong governance, policy integration, and local engagement, factors that are often overlooked in conventional peatland studies.

This system-thinking approach presents a novel way to analyze the interconnected dynamics of peatland management. Many of the existing studies focus on individual aspects of degradation such as carbon loss, biodiversity impacts, and climate change. This review offers an integrated approach by linking environmental consequences, socioeconomic drivers, and governance efforts. By emphasizing how governance, economic forces, and ecological restoration interact, this work fills a critical gap in current knowledge and offers a comprehensive view of climate resilience.

6. Conclusions

This paper emphasizes the critical importance of sustainable peatland management for climate change mitigation and ecosystem service preservation. It highlights the significant negative impacts of peat extraction, including carbon dioxide emissions, and details the European Union's comprehensive policy response. These policies aim to protect, restore, and sustainably manage peatlands, considering the varied European contexts and advocating for a phased, location-specific approach to meet restoration objectives. Additionally, the need for decision-support tools for selecting sustainable management techniques based on geographical specifics is underlined.

The review provides a detailed analysis of peatland management within European environmental policy frameworks, highlighting the essential role of peatlands in ecological balance and the need for concerted sustainable management and restoration efforts. It calls for ongoing research, innovation, and collaboration to address peatland degradation and underscores the EU's commitment to ecological sustainability and climate mitigation, advocating for the potential of peatlands as vital natural resources. Moreover, it has shown that the complexity of variables influencing carbon dynamics within the peatlands underscores the necessity for a specialized assessment tool that guides the selection of the most appropriate restoration strategy, balancing ecological, hydrological, and socioeconomic factors. This comprehensive and multidisciplinary approach ensures the sustainability and efficacy of restoration efforts, aiming to maximize environmental benefits while considering the broader impact on local communities and economies. To ensure the long-term sustainability of the peatland ecosystems, we emphasize the following key recommendations: enhanced monitoring and decision-support tools; stronger policy integration and enforcement; targeted financial support for restoration; investment in sustainable alternatives; and stakeholder engagement and public awareness.

In light of these findings, it is evident that the future of European peatlands will depend on how effectively ecological restoration is integrated with economic and policy frameworks. Beyond restoration, there is a need to reimagine peatlands as multifunctional landscapes that can simultaneously deliver climate mitigation, biodiversity conservation, and socioeconomic benefits. Moving forward, a transformative shift is required—from reactive protection to proactive ecosystem design—where sustainable land use, paludiculture, and circular bioeconomy models are prioritized. As such, peatlands should no longer be viewed as extractive resources but as climate assets and innovation platforms. Bridging the gap between science, policy, and practice will be crucial, and this review aims to serve as a foundation for more integrated, adaptive, and forward-thinking peatland strategies across Europe.

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sustainability

MDPI

Review

Material Sustainability of Low-Energy Housing Electric Components: A Systematic Literature Review and Outlook †

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† This paper is an extended version of our conference paper from the 4th LA SDEWES Conference, Viña del Mar, Chile, 14–17 January 2024 and WSED 2024, Wels, Austria, 5-8 March 2024.

Abstract: As part of the energy transition, near-Zero-Energy-Buildings use electric systems that reduce emissions and consumption. Nevertheless, the increased use of such systems comes with the E-waste challenge. Circular Economy concepts try to make more efficient use of these materials, but sustainable evaluations mainly focus on energy and emissions. The developed automated text analysis tool quantifies the appearance of circularity concepts in open-access literature about different stages of production, use, and end-of-life for heat pumps, Lithium-Ion batteries, photovoltaic modules, and inverters. The energy focus is corroborated in different amounts depending on the component and stage, and when circularity concepts appear, they are centred on waste and recycling. Numerical variables to model environmental impact available in open-access literature are limited, generalised, or present in a wide range. Access to product environmental specifications should be encouraged to ensure that energy transition is sustainable in all its dimensions.

Keywords: Circular Economy; sustainable energy; photovoltaic systems; heat pumps; sustainable evaluation

1. Introduction

Buildings have a significant potential to fight climate change, as worldwide, they account for around 38% of energy-related CO_2 emissions [1]. Consequently, the EU required that all new buildings should be 'Nearly Zero Energy Buildings' (nZEB) by 2020 [2]. These use a set of energy strategies that frequently include renewable energy, usually photovoltaic (PV), efficient heating/cooling, as well as forced ventilation [3] or automation [4]. Examples of sustainable houses in different contexts, Australia [3], Japan [5], and the United States of America [6], are concluded to be environmentally and financially advantageous while also improving living conditions.

Nevertheless, overcomplicating systems could lead to efficiency loss [7], and high resource use and reliability should be considered as there can be simpler vernacular alternatives to high-tech automation [4]. Critiques can also be made as when modelling and optimizing PV [8] and heating [9], focus is given to cost and CO_2 emissions. However, in sustainability, there are many other factors to consider, as shown in Life Cycle Assessment (LCA). This approach shows different environmental indicators, which may include End-of-Life (EoL) challenges for Lithium-Ion Batteries (LIB) [10], overall higher impacts excepting emissions for heat pumps (HP) [11,12], or land use, emission, and water use challenges for PV [13].

Material use and its implications are generally neglected, but they are especially interesting for these electrical components due to their potential role in the development model [14]. As the electrification of building energy systems and E-waste continues to increase, it is of interest to study how Circular Economy (CE) concepts are incorporated into sustainable evaluations of energy systems of the energy transition.

Individual components of these systems and specific CE strategies are extensively treated in the literature, but their evaluation as a whole, including all possible combinations of strategy/component and their implications, is not well documented. Review papers try to gather and summarise the literature, but they tend to fall into the same component specificity problem. Accordingly, a systematic evaluation would be beneficial to assess and prioritise possible measures.

Therefore, the challenge is to holistically assess the current research focus, identifying trends and gaps in an automated manner and representing them quantitatively, such that comparing different technologies is more accessible. Thus, the objective is to evaluate sustainability and CE concepts in qualitative and quantitative trends in research papers about electrical systems used in nZEBs. For this, qualitative trend analysis should be conducted in a systematic and automated way, and corresponding quantitative values needed to model such systems should be manually identified.

2. Methods

Qualitative and quantitative trends have different approaches, as they have different focuses. These are described in the following points.

2.1. Qualitative Trends

Qualitative trends in a research topic can be monitored by the frequency of appearance of specific keywords or indexes. This does not refer to the result of the evaluation but only if the subject is being addressed. Examining words that are present in a text and then relating them to a research topic is difficult, as separation from contextual and thematic words needs to be achieved manually or by advanced classification methods. Topic detection tools are available, but they require the use of external servers or processing algorithms that cannot always be customised. Alternatively, a common and locally feasible approach are Wordclouds, which present words by frequency after cleaning a text from connectors. Applying this to 241 open-access research papers shows results that are more general than expected, as shown in Figure 1.

Therefore, a second option is to look for specific representative words that characterise a particular research topic and then find them in the text. These representative keywords can be selected from a set of sustainability evaluation methods defined by the literature. Sustainability keywords can be taken from LCA, as it is a methodology to evaluate a project through its complete life. A set of elements to consider is stated by the German Institute for Standardisation [15] and the European Commission [16]. For CE, keywords can be obtained from one of its many definitions, e.g., "...a design for repairing, remanufacturing, refurbishing, or recycling to keep products, components, or materials circulating in and contributing to the economy..." [17] or 10 R definition [18]. Also, in the Ellen Macarthur Foundation butterfly diagram, maintaining, prolonging, refurbishing, remanufacturing, and recycling are important cycle subloops [19].

Finally, evaluated technologies used as active strategies in nZEBs are heat pumps, Lithium-Ion batteries, PV inverters, PV modules, and PV systems. Evaluated methods are 'life cycle assessment', 'circular economy', 'manufacturing', 'degradation', 'reliability', and 'end-of-life'. Each search consists of all possible combinations of methods and technologies.

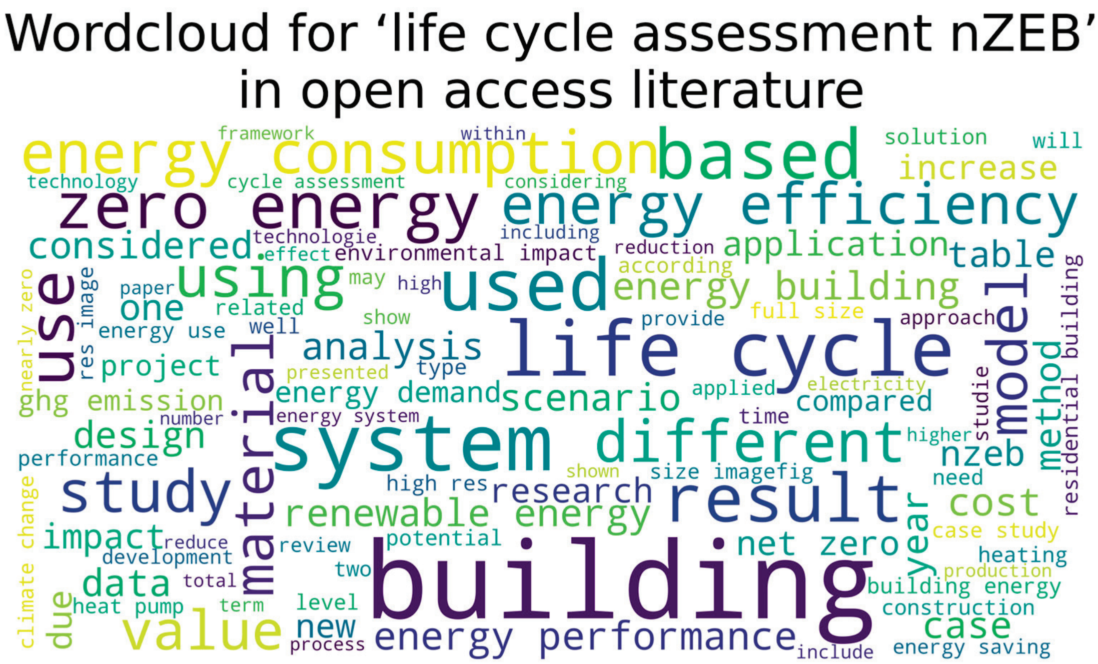

Figure 1. Wordcloud for "life cycle assessment nZEB", mostly generic words are identified.

2.2. Text Processing

Processing was performed with Python. To have a good article corpus, systematic separation by topic needs to be conducted over a vast number of available open-access candidate articles. To achieve this, article filtering is conducted by searching for words' frequency of appearance in the text. Trends can later be identified by counting input indexes obtained from previously mentioned concepts. The process workflow can be summarised in Figure 2.

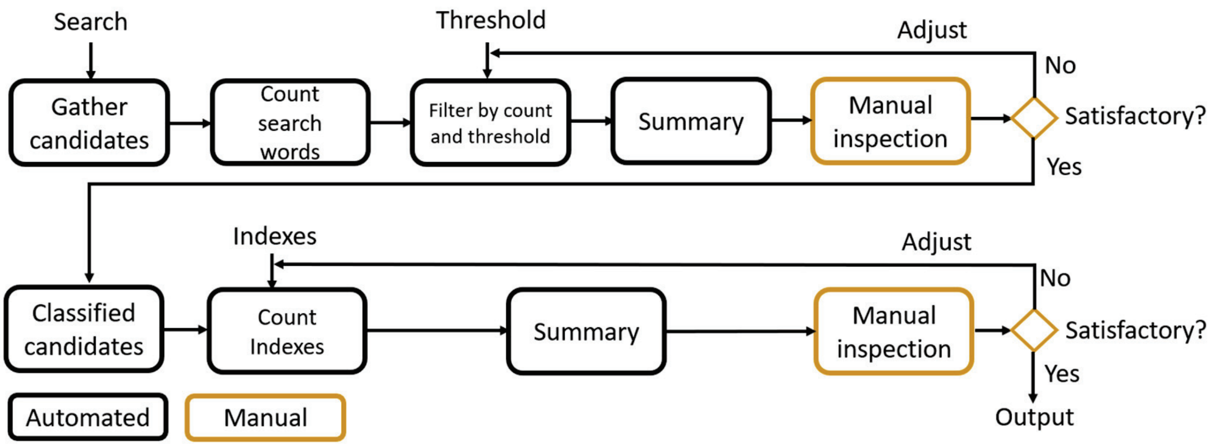

Figure 2. Workflow of article processing and manual intervention reduced to the minimum possible.

To obtain better text classification, shorter texts were prioritised; therefore, long "institutional reports" and theses were ignored. This also helps to reduce the number of possible article sources into better sources, thus helping systematisation. Accordingly, the three sources of papers for this research were ResearchGate, ScienceDirect, and MDPI. Open-access papers are downloaded by search, with each search acquiring between 200 and 230 raw candidates. Taking "Life cycle assessment heat pump" as an example yielded five candidates from MDPI, ResearchGate (twenty-two candidates), and ScienceDirect (two hundred candidates), with a total of 219 candidates after removing duplicates.

Once the text of the papers is extracted (images are ignored), a count of search keywords is used to determine if the paper is on the right topic. Following the example, for each paper, a count of 'life', a count of 'cycle', a count of 'assessment', a count of 'heat', and a count of 'pump' would be completed. This count is in lowercase and eliminates special characters, thus reducing the number of possible combinations. This search count is then divided by the total paper word count in order to compare papers with different lengths. This is presented as appearances per 10,000 words; hence, the numbers are not too small. If all input search words are above a certain threshold (30 for LCA, 20 for degradation, and 15 for CE; manufacturing, EoL, and reliability, appearances per 10,000 words), then the paper is considered acceptable for the analysis. Finetuning the threshold requires a quick manual review of paper titles and keyword appearances. Taking the paper "Environmental Life Cycle Assessment scenarios for a district heating network. An Italian case study" [20], the search word 'life' appears 79.7 times per 10^4 words, 'cycle' 70.24, 'assessment' 54.03, 'heat' 229.64 and 'pump' 81.05. Thus, this paper would pass the filter.

The same counting procedure is applied for indicator keywords, but no further action is taken. In the given paper example, results for 'climate change' were 18.91 appearances per 10^4 words, 'ozone depletion' 4.05, 'ionizing radiation' 6.75, 'photochemical ozone formation' 4.05, 'particulate matter' 4.05. The output of the process is a table where each paper is a row, and each index is a column. Each cell is a count per 10^4 words of the index on that paper.

This search is attained with "find in text" on a text striped from spaces, special characters, and break lines, and not with "word is", as some words can be deformed by the pdf formatting-extraction. This finding modality implies that searching for acronyms can lead to many false positives; therefore, they are avoided. Another challenge is that word conjugation, alternative spelling, or synonyms are not directly recognised. Nevertheless, this can be manually corrected by adding words to the "keyword list" but using the word root to include plurals and conjugations, also known as stem (recycl: recycle, recycling, recycled) or by including alternative wording of the search (end-of-life: decommissioning, . . .).

2.3. Quantitative Parameters

To complement this, quantitative values to model such systems are researched. These values would potentially be used to calculate material and energy inventories required to predict economic outputs and environmental impacts.

Material inventories mostly relate to the material needed to manufacture, operate, and decommission systems. Examples of operation and maintenance could also be lubricants, refrigerants, or cleaning fluids while repairing soldering or sealants. Replacements of complete components are also needed due to the EoL of cables, batteries, or modules; therefore, the lifetimes of components are also considered. After EoL, treatment options and efficiencies need to be accounted for. This could be in the form of repurposing, remanufacturing, upgrading, or recycling, but most commonly by disposal. This point is also associated with production energy per constituent part or by material mass.

Energy inventories refer to the amount of energy these systems generate/consume. Besides design capacities, degradation and operational times are required. Therefore, failure and repair times are again needed.

As the desired output of each component is different, each variable can be expected to be found and normalised in different units besides time, with thermal output and electric input in HPs, electric output and area for PV modules, electric output power and weight for inverters, or storage capacity and weight for LIBs.

Values for these parameters are manually searched by exploring accelerated ageing tests, manufacturer technical sheets, and "statistical" logs literature of specific components. Finally, for each technology, the following values are searched: Manufacturing: Material and Energy; Ageing: Lifetime, Degradation; Reliability: Failure, Repairability; Decommissioning: Recycle, Waste, Energy.

3. Results

Applying the aforementioned methods, the following results were obtained.

3.1. Qualitative Trend Results

Results are obtained with available papers until June 2023. The final number of articles after filtering can be summarised in Figure 3. It can be directly noted that some methods and technologies have more available matches. This is also noted as concepts such as decommissioning and ageing were originally tested with unsuccessful results. PV inverters show a low quantity of matches, while batteries have the most. EoL has the least number of matches by analysis mode, while degradation is significantly higher, especially for LIBs and PV modules. Additionally, 'life cycle assessment nZEB' was also searched with 13 total matches.

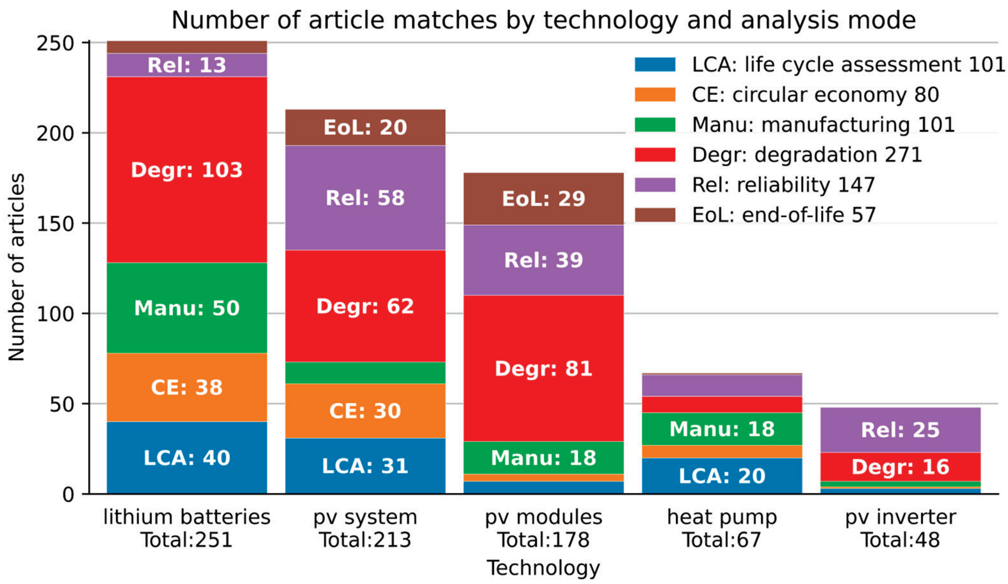

Figure 3. The number of article matches by technology and analysis mode. Lithium batteries have an overall number of papers addressing them, while inverters are the least. End-of-Life is the least frequent analysis mode.

Life cycle assessment: Technology average word count from original LCA indexes indicates a focus on 'climate change' with 5.4 per 104 words, followed by 'acidification' (1.6), 'land use' (1.1), and 'ozone depletion' (0.9) as the main topics of interest. Overall, 'Heat pump' addresses more indexes and more often. Oppositely, 'PV inverter' addresses fewer indexes, with only significant 'climate change' and 'land use'. Technology disaggregation can be seen in Figure 4.

Using the six most frequent synonyms and alternative wording found, average numbers across technologies improve for the 'material' group, increasing to 11.9, but 'emission' still triples it with 43.5. One noticeable exception (besides the 'material' concept) is 'recycle', especially for LIBs. Other concepts tested with limited success were specific materials and metals, LCA midpoints and methodologies, or indicator units. This is visualised in Figure 5.

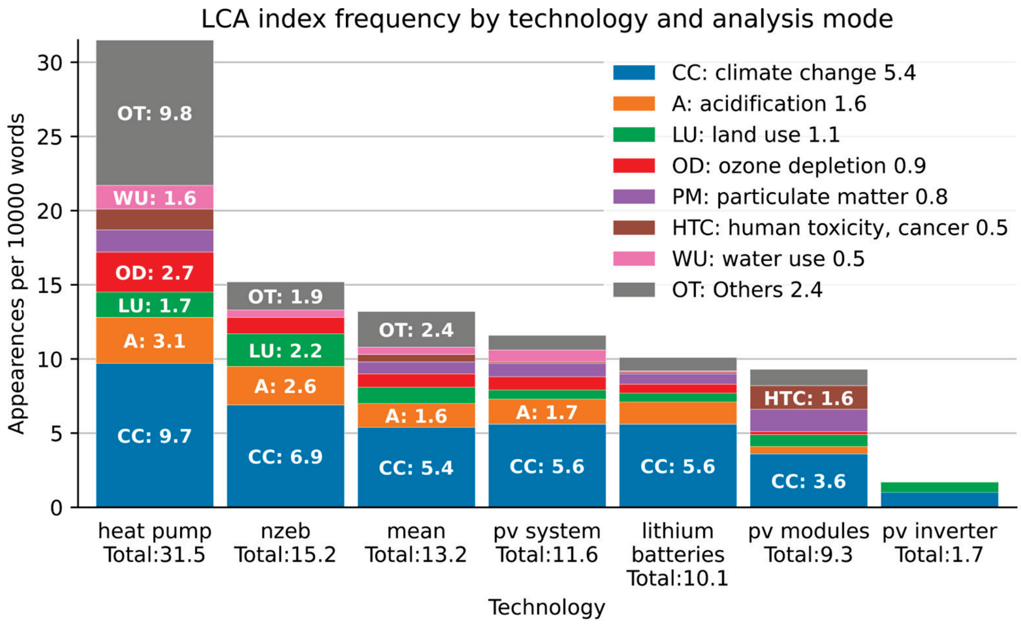

Figure 4. LCA index frequency by technology and analysis mode. Heat pumps treat more environmental impact categories, and more often, the opposite happens to inverters. Climate change is the most common impact category.

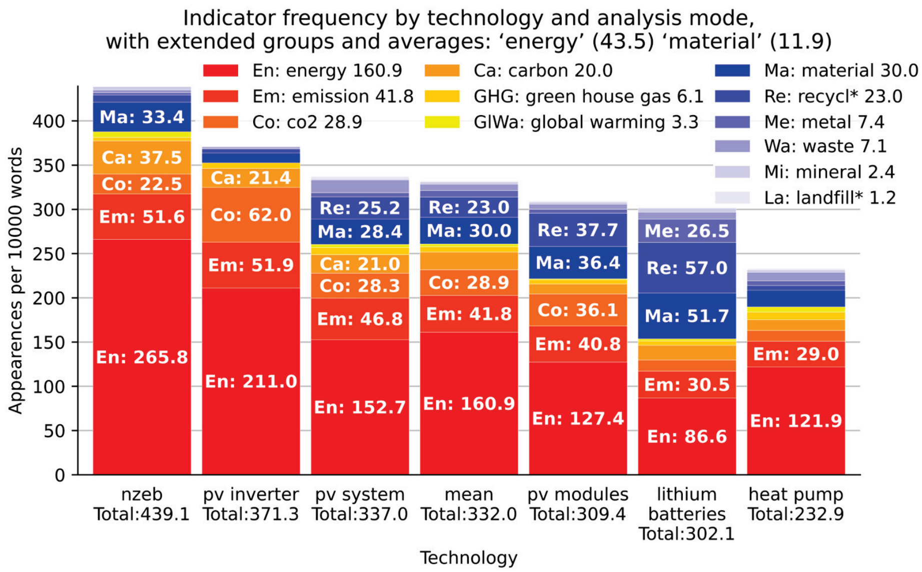

Figure 5. Indicator frequency for extended 'material' and 'energy' concepts by technology and analysis mode, with group average. The 'energy' group is higher than the 'material' group by around 4 times, with the exception of Lithium-Ion batteries. Stemmed words marked with *, representing multiple possible endings.

Circular Economy: Ignoring 'PV inverter' due to low count, 'heat pump' reaches overall less frequency. As summarised in Figure 6, 'recycle' (63.3) has the most appearances for technology average, followed by 'design' (42.7) and 'material' (26.0). These three already accumulate 53% of the overall matches. In technology, disaggregated values such as 'recycling' and 'material' gain specific importance for LIBs and PV modules. The category 'others' includes concepts of maintaining, prolonging, redistributing, refurbishing, remanufacturing, and adapting.

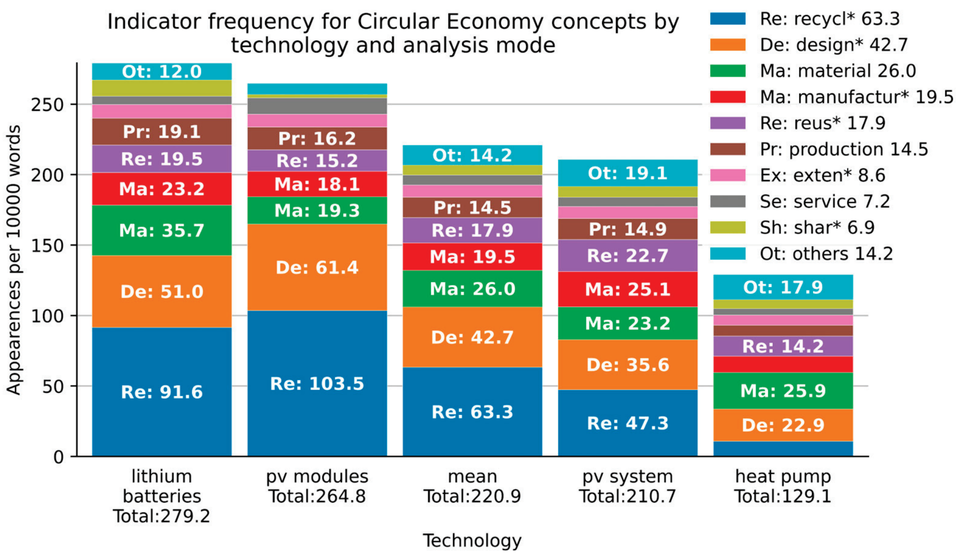

Figure 6. Indicator frequency for Circular Economy concepts by technology and analysis mode. Recycling is the most quoted term except in heat pumps. Stemmed words marked with *, representing multiple possible endings.

Using alternative wording for 'waste', 'regulation', and 'business' groups, 'waste' as a group and word maintains its importance, especially for PV modules. 'Regulation' and 'business' together account for roughly 50% of the average findings. Further concepts tested were 'legal', 'legislate', 'politics', and 'norm' for regulation, while for business, 'driver', 'enabler', 'profit', 'investment', 'job', and 'uncertainty'. Finally, this is shown in Figure 7.

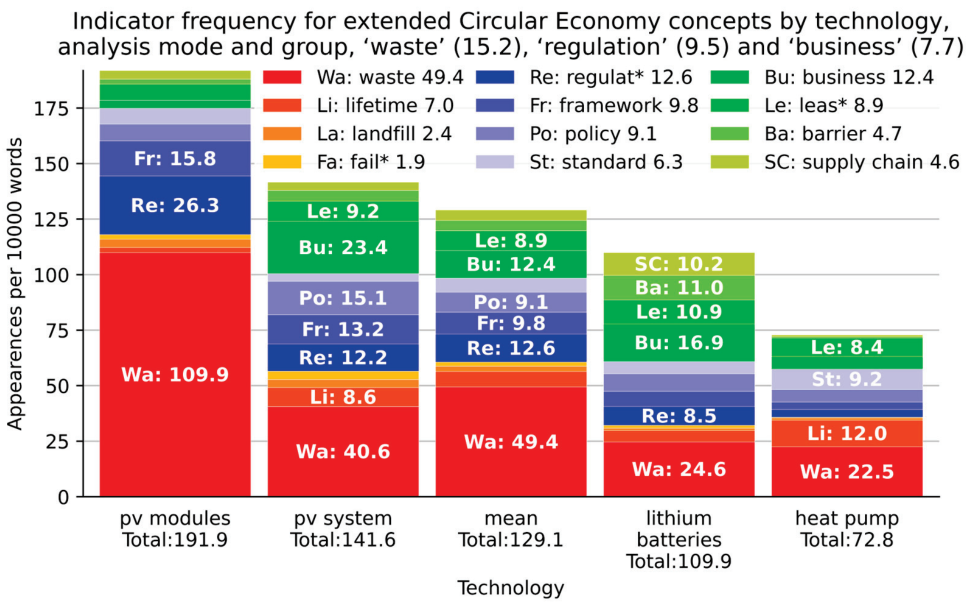

Figure 7. Indicator frequency for extended Circular Economy concepts, 'waste', 'regulation', and 'business' top four more frequent concepts by technology and analysis mode, with the group average. Waste the most quoted concepts across all technologies. Stemmed words marked with *, representing multiple possible endings.

Manufacturing: Figure 8 presents the five most frequent manufacturing concepts grouped in 'energy', 'manufacturing', and 'material', showing an overall focus on energy, whereas a group accounts for around half of the appearances. Nevertheless, material concepts gain importance in 'PV modules' and 'LIBs'. 'Manufacturing' as a word appears more often than 'material', but specific manufacturing processes do not appear frequently enough to be influential. Other tested concepts were specific materials contained in components, manufacturing processes, and machinery.

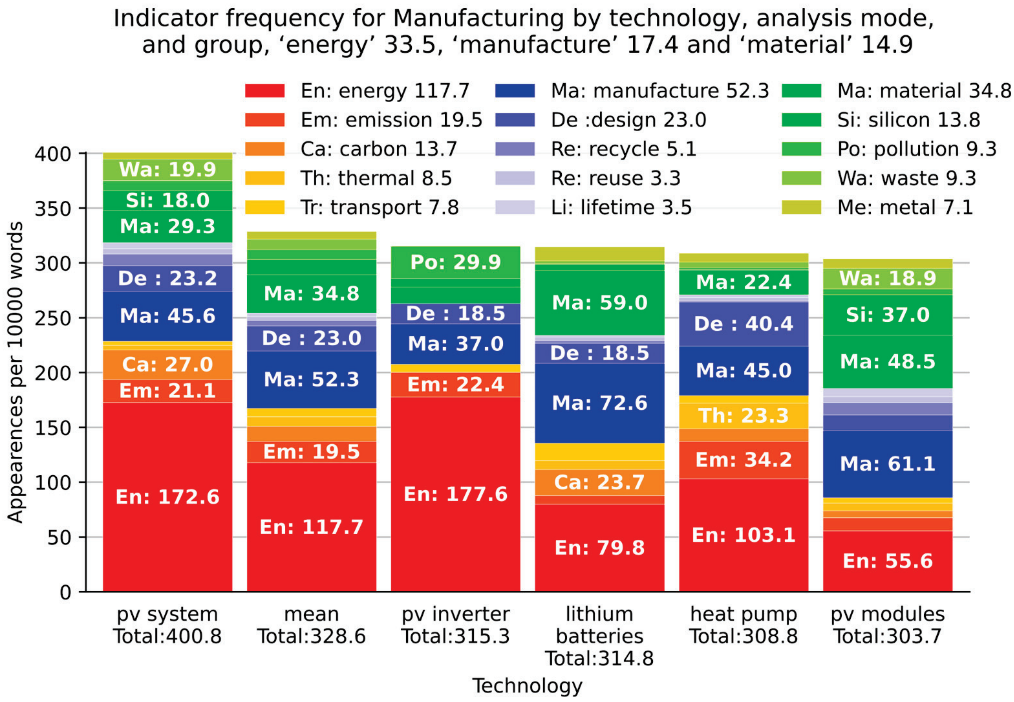

Figure 8. Indicator frequency for manufacturing: The top five most frequent concepts by technology and analysis mode, with group average. The 'energy' group presents most of the occurrences.

Degradation: Most degradation-related concepts focus on 'efficiency', especially for heat pumps. Specific modes of fail/deterioration only appear after 'fail' and 'lifetime', with 'cracking' and 'corrosion' for 'PV modules' and 'resistance' for LIBs. LIBs in literature present more specific chemical modes of degradation and failure, which are not represented under these indicators (see Figure 9).

Reliability: For reliability analysis, the words 'fail' and 'lifetime' gain particular importance as they represent 56% of all average matches. This is especially noticeable for 'PV inverters'. Only one specific failure mode is significant, with 'cracking' for PV modules (see Figure 10).

End-of-life: Heat pumps and inverters are excluded from the analysis due to low count. 'Recycle', 'waste', and 'recover' account for 75% of all matches. LIBs are especially centred towards 'recycling' with 46% of their matches. Other tested concepts were alternative CE EoL options such as 'repair', 'upgrade', 'downgrade', 'repurpose', 'remanufacture', and 'refurbish', as well as 'incinerate', 'collect', and 'landfill' (see Figure 11).

3.2. Quantitative Trend Results

For precise modelling and calculation of the life cycle impacts and circularity potentials of nZEBs as a system, numerical variables for the aforementioned elements need to be identified. Repairability numbers in open data were scarce; therefore, they were omitted. Other inconclusive points are also skipped. Obtained values are commented on.

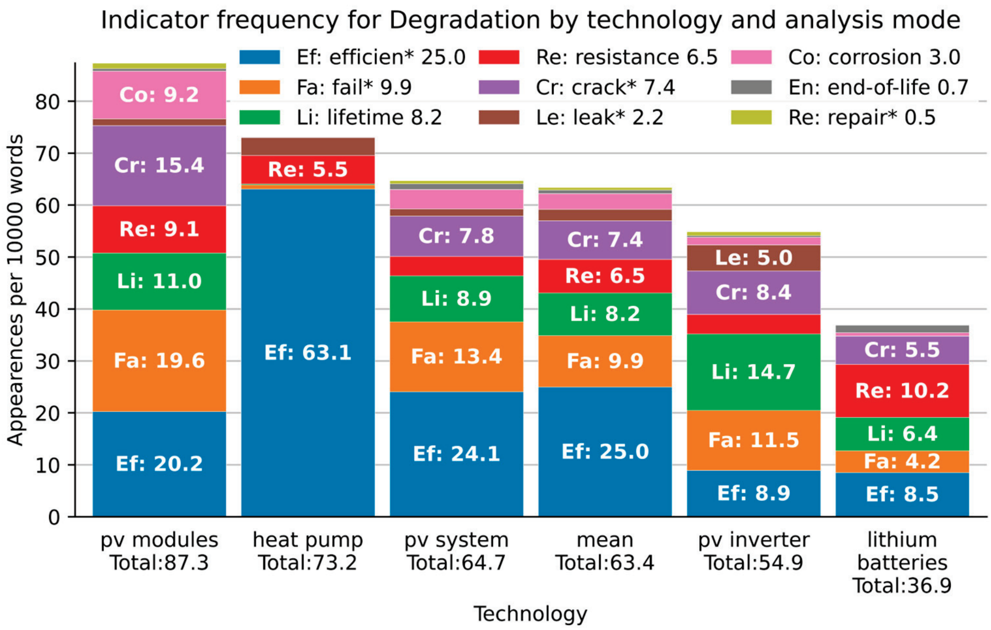

Figure 9. Indicator frequency for degradation by technology and analysis mode. Efficiency is the most important topic, especially for heat pumps. Stemmed words marked with *, representing multiple possible endings.

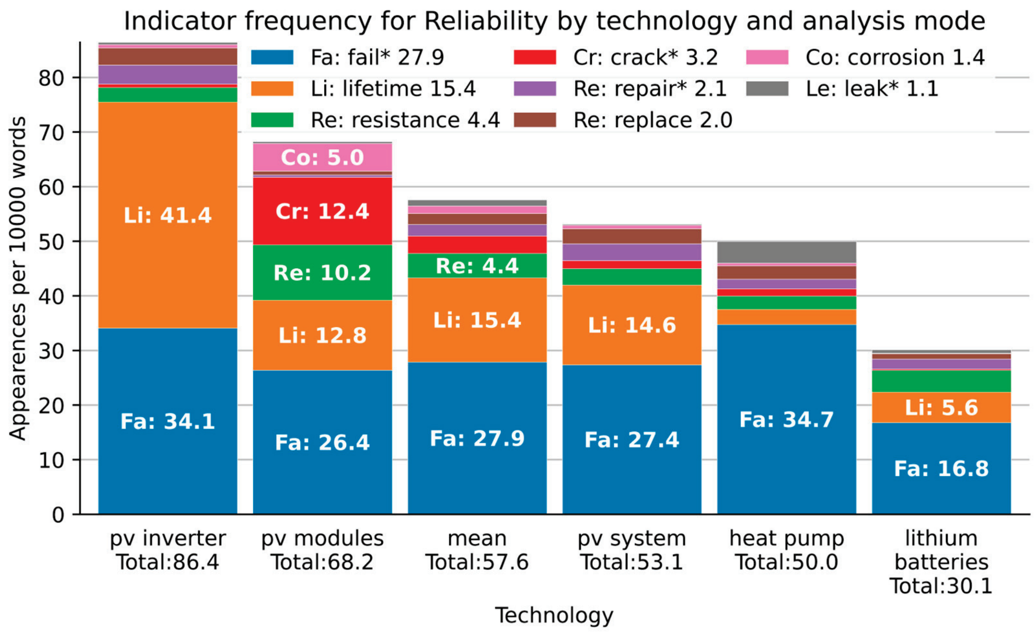

Figure 10. Indicator frequency for reliability by technology and analysis mode. 'Fail' and 'lifetime' are the most common concepts. Stemmed words marked with *, representing multiple possible endings.

3.2.1. PV Module

Manufacturing Material: These are needed to calculate energy input and possible recycling rates. The material depends on technology, but a common distribution by weight is glass 68–85% and aluminium 10–14%, followed by plastic and copper, with sources for Silicon (Si) [21], Si and Cadmium-telluride (CdTe) [22], while [23] gives even up to 95% glass to CdTe panels.

Manufacturing Energy: mainly relates to emissions, where manufacturing step and place of production play a significant role. Production is dominated by electric energy with some traits of natural gas and coal [22], but as most cells are produced in China, where a higher emission rate needs to be taken into account [24]. Transportation should also be added to these values. An average of 3392 MJ/m^2 in a range between 2513 and 5253 MJ/m^2 is calculated for different module technologies and years [25] (2017), [26] (2006), [27] mono and polycrystalline Si (2014). Others also state per Wp or by module.

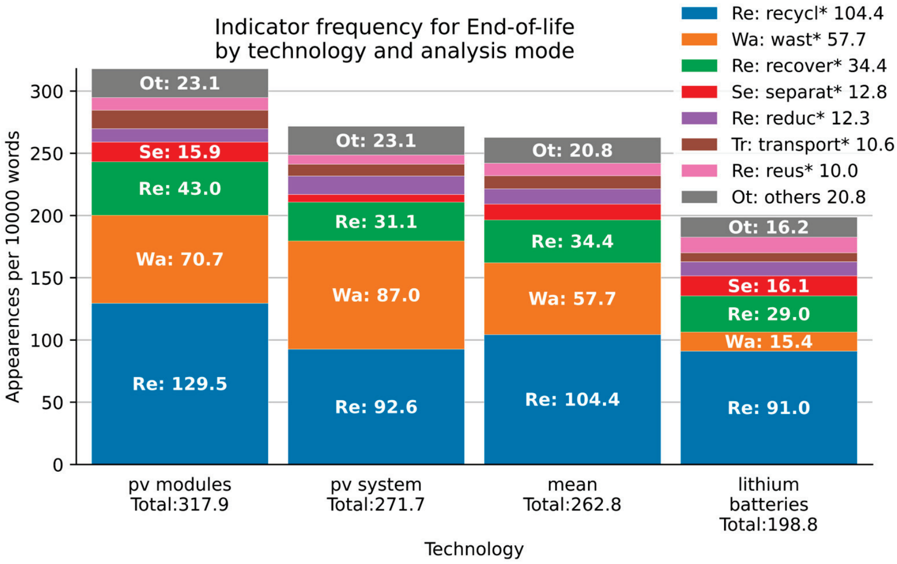

Figure 11. Indicator frequency for End-of-Life by technology and analysis mode. 'Recycle' and 'waste' are the most common concepts. Alternative CE EoL modes are not relevant in the literature. Stemmed words marked with *, representing multiple possible endings.

Lifetime: Most projects consider a lifespan of 25–30 years [22], with [28] considering up to 35, but [29] suggests that real values corrected by economic or practical reasons can be between 15 and 20 or even 7 years [21]. Climatic conditions and sociocultural conditions are not always explicitly addressed for lifetime selection.

Degradation: A degradation rate of around 0.8% per year is often used [30], as it is the mean rate of a skewed distribution for different technologies [31]. An updated version [32] also includes weather categories for Si modules with a range for upper and lower bounds of the interquartile range between 0.2 and 1.5%/year. Additionally, ref. [33] gives distributions by climatic zone and degradation mode.

Failure: Failure distributions for complete PV systems are presented by [34] with a range of 0.0046–26 (10^{-6} failures/year) for different system components, while [35] gives distributions. More detailed causes and comments on failure sources and climatic conditions are presented in [36], ranging between 0.0152 and 0.065 (10^{-6} failures/unit-h).

EoL waste and recycling: Most elements can be highly recovered in PV modules with a yield of over 80%, except plastic [37]. To this, ref. [38] adds tin with 60% recycling yield but neglectable mass share (0.12%). The EU targets 65% of the weight of products on the market or 85% of waste, with 80% of it recycled or ready for reuse [23], but worldwide, only 10% is recycled [38].

PV technology is a quickly evolving field, visualised by the rapid cost decrease and growing global production capacity [22]. A disadvantage of this is that constant changes in technological capabilities make the use of precise historical indicators challenging. Even though there are studies on specific topics for more accurate modelling and values, it is common to use average numbers. These are commonly abstracted from their usage conditions, climatic zones, or cultural environment.

3.2.2. Inverter

Manufacturing Material: Weight material distribution is given in [39], with different power capacities having different weights. Table 1 summarises this per kg/kW.

Table 1. Material distribution of PV inverters kg/kW.

Kg/kW	Min	Mean	Max
Total weight	2.31	4.15	7.48
Copper	0.39	0.89	2.20
Aluminium	0.56	1.29	2.00
Steel	0.18	0.99	3.92
Other individual components	0.12	0.55	0.88
Printed board assembly	0.25	0.42	0.68
Printed wiring board	0.07	0.13	0.28

Manufacturing Energy: The same authors [39] also give energetic manufacturing needs for different power sizes and fuels, with total values normalised to kW range between 10.4 and 20.5 MJ/kW, with an average of 15.1.

Lifetime: 15 years are estimated, but these are highly dependent on weather, PV module degradation, and installation location (indoor vs. outdoor) [40], while [41] gives time-to-fail probabilities with rough ranges depending on survival probability and manufacturer, ranging between 6 and 18 years. The effect of load ratios and temperatures on lifetime is also considered in [42].

Failure: In [43], inverters present the most prominent failing rates among PV components, with [34] giving failure rates between 11 and 180 (10^{-6} failures/year), with an average of 44. Accordingly, ref. [42] states that inverter failures accounted for 36% of lost energy, while modules only 5%.

Analysis for inverters tends to be focused on failure and reliability as it is one of the most failing components of the system. Other topics of interest are difficult to find.

3.2.3. Lithium-Ion Battery

Manufacturing material: For a 7 kg battery with a 1.4 kWh capacity, the primary material used as weight percentage [44] is 25% NMC111 powder (Lithium-nickel-manganese-cobalt Li-Ni-Mn-Co oxides), 15% graphite/carbon, 11% copper and 25% aluminium. A range between 40.5 and 50.1 kWh/kg is given by [45] for a different battery.

Manufacturing energy: for the same battery [44], the total energy is 1126 MJ or 44.6 kWh/kg, and CO_2e emissions (72.9 kg) have a very similar distribution, with 38% coming from NMC111, 17% aluminium, and 19% from cell production.

Lifetime and degradation: EoL of a battery is defined as reaching 80% of original capacity due to degradation without catastrophic failure. Up to 20 years can be expected [46], but the actual degradation could reach 8 years [30] and vary over technologies [47]. There are calendar [46], cycle [48], and varied approaches [49] degradation models, where the most influential variables are:

Full Equivalent Cycle (FEC): It can be understood as the amount of energy that the battery has given compared to its nominal capacity. As most of the degradation methods are caused by cyclical charge and discharge, an overall more used battery will have a reduced capacity. State of Charge (SOC): Refers to the amount of energy stored at a moment in the battery. If this is high, it means there is a high potential between the anode and cathode, accelerating cell degradation. For operational use, a medium average SOC is preferred. Depth of Discharge or Cycle (DOD or DOC): Similarly, when SOC levels are too low (the depth of the discharge is high), there is a tendency for capacity loss; thus, high DOD is avoided. C-rates: A high C-rate, or speed of charge/discharge relative to the capacity, will reduce capacity and increase resistance, even for the same FEC with a low C-rate. Temperature: Working temperatures are expected to range between 15 and 35 °C, as high temperatures due to charging or the ambient can degrade the battery. Low operating temperatures can also reduce cell capacity and efficiency. Therefore, real lifetimes will depend on usage conditions.

Failure: According to [34], a range of 9–11 (10^{-6} failure/year) is documented for general batteries.

EoL waste and recycling: Following [50], recovering rates can be summarised by material as (min-mean-max): Li 60-89-100, Co 64-89-100, Mn 91-95-99, Ni 94-98-100. Nevertheless, collection rates reached 5% in 2016 in the United Kingdom and 45% in 2015 for 12 countries in the European Economic Area [51].

The use of Lithium-Ion batteries in e-mobility offers a broader range of studies. Degradation studies are present, but average values are still used for a PV project's lifetime. The main sustainable treatment by EoL is recycling, although real access to service is not clear or widespread.

3.2.4. Heat Pump

Manufacturing Material: Total manufacturing materials depend on the type of heat pump exchange type (Air, water, ground), assuming a capacity of 10 kW [52], summarised in Table 2.

Table 2. Material needs (Kg) of Heat Pumps according to exchange medium.

Part	Material	Air	Water	Ground
HP	Steel	152	95	95
	Copper	37	22	22
	Elastomere	16	10	10
	Refrigerant	5	3	3
Underfloor heating system	Sand	4600		
	Cement	900		
	Aluminium	126		
	LDPE	101		
	Polystyrene	66		
Collector	Ethylene glycol		274	267
	Brass		7	7
	Cast Iron		43	
	Cement		1	19
	Steel		33	33

Lifetime: A report from 2014 suggests that the most used value is 20 years, but values between 25 and 30 would be more realistic [53].

Failure: Most common and costlier failures are shown in [54], but not dependent on other variables (time, cumulative output, etc.). For degradation, between 0.25 and 1 are identified [55].

EoL waste and recycling: Recycling-to-landfill ratios are given in [54], where steel gets 61.7% recycled, aluminium 90%, copper 41%, refrigerant 80% reused, and ethylene glycol 100% to wastewater treatment. Meanwhile, plastics, sand, brass, and cement are 100% landfilled.

Heat pump material use and recycling potentials are clear, but lifetimes and failures are not clear or often assumed.

Finally, ranges for desired search combinations, with commented limitations, can be summarised in Table 3, where '*' are inconclusive values and empty for not found.

Table 3. Search combination results (min, average (or mode), max).

Component	1 Manufacturing Material Energy	2 Ageing Lifetime Degradation	3 Reliability Failure	4 Decommissioning Recycle and Waste Energy
Module	Mass distribution given. (68-*-95) % mass is glass, (2.5-3.4-5.3) GJ/m^2 for different technologies and years	(7-20-30) years, (0.2-0.8-1.5) %/year. Bigger ratios found, but unusual	(0.0046-*-26) 10^{-6} failures/year	(*-80-*) % mass, ()
Inverter	kg/kW ratios per material given, aluminium is the most intensive one, ranging (0.56-1.29-2.00), (10.4-15.1-20.5) MJ/kW	(6-15-18) years, ()	(11-*-180) 10^{-6} failures/year	(), ()
Battery	For a 1.3 kWh 7 kg LIB (25% NMC111 powder, 25% aluminium) % mass, (40-*-50) kWh/kg	(8-*-20) years, (degradation models)	(9-*-11) 10^{-6} failures/year	(60-*-100) % mass recovering rate for different materials with collection (5-*-45) %, ()
Heat pump	(95-*-152) kg steel without a heating system and collector ()	(20-20-30) years, (0.25-*-1) %/year	()	Recycling ratios per material given (41-*-90) % of mass recyclable, ()

3.3. Environmental Impacts

Environmental impacts in LCA results are presented according to a Fundamental Unit (FU), which for energy systems usually is energy generated or consumed. This means that the same product, under different usage or weather conditions, could report EIs varying significantly even if manufacturing and EoL are the same.

For PV systems, manufacturing accounts for the most important share [13]. During the use stage, land use could be an issue, but considering domestic and roof-top installations, this could be ignored.

Most of the energy and material required for PV modules are related to high-quality glass and aluminium. Additionally, other impacts can also be found in part due to the use of critical raw materials such as Ga, Ge, In, and Sb, among other raw materials [13,22]. From a CE point of view, materials gain special relevance depending on the definition; this can be represented by "resource use, mineral and metals" or "abiotic resource depletion", which relates production rates to reserves [56]. Materials are also important, considering supply chain bottlenecks and competing final uses [14]. Thus, even if recycling may not always be percentage-wise significant for EI reduction [28,57], it is still important to diversify sources and reduce waste. Water use is another resource required in the chemical processing and recycling processes of raw materials. Nonetheless, PV is still one of the least water-consuming sources of energy [13].

Lithium batteries have many combinations of materials for anode, cathode, and electrolyte materials [50]. Acknowledging this, commonly used materials with environmental significance are cobalt, lithium, and nickel. Cobalt is mainly produced in DR Congo, where illegal, artisanal, or small mining is considerable. Its real impacts are unknown, but their release of heavy metals causes health issues. Lithium extraction causes water issues in the high plains of Argentina, Bolivia, and Chile, where it is extracted from brine. In Australia and China, it is extracted from hard rock, which also requires water and energy and generates waste rock. Nickel production is related to acid rain, heavy metal contamination, particulate matter, and water pollution. To all of these EIs, the social implications of raw material mining and illegal E-waste treatment should also be considered [58].

In the case of HPs, the major source of EIs is the use stage [59]; therefore, consumption patterns and electricity mix play an important role, unlike manufacturing and EoL. Refrigerant leaks in the use stage also generate global warming potential and ozone depletion challenges [60].

3.4. Selection of Relevant Literature

Considering the previous methods, values, and limitations, literature on the direction of addressing identified gaps is presented in Table 4. These should work as examples of modelling trade-offs, statistical research, identification of keywords, or general CE inspiration.

Table 4. Selection of relevant literature that partially addresses identified gaps.

Title	Year	Method	Analysis	Main Takeaway
Economic Lifetimes of Solar Panels [21].	2022	Modelling	Module lifetime	Real lifetime can be shorter than technical values due to economic reasons
Compendium of Photovoltaic Degradation Rates [32].	2016	Statistical description	Module degradation	Real degradation rates depend on the use conditions
Reliability, Availability and Maintainability Analysis for Grid-Connected Solar Photovoltaic Systems [34].	2019	Modelling/Statistical description	System failing	Failing distribution of components in PV systems
Failure Rates in Photovoltaic Systems: A Careful Selection of Quantitative Data Available in the Literature [36].	2020	Statistical description	System failing	Failing distribution of components in PV systems, inverter most failing.
Life Expectancy of PV Inverters and Optimizers in Residential PV Systems [41].	2022	Statistical description	Inverter lifetime	The survival probability of inverters depends on using conditions
PV System Component Fault and Failure Compilation and Analysis [43].	2018	Statistical description	System failing	Failing distribution of components in PV systems, inverter most failing
Aging Aware Operation of Lithium-Ion Battery Energy storage Systems: A Review [49].	2022	Modelling	LIB degradation	Degradation factors and models for LIBs
The Common and Costly Faults in Heat Pump Systems [54].	2014	Statistical description	HP failing	The most common faults in HPs are in compressors
Environmental Life Cycle Assessment of Heating Systems in the UK: Comparative Assessment of Hybrid Heat Pumps vs. Condensing Gas Boilers [11].	2021	Modelling/LCA	HP LCA	HP is better in emission but worse in other EI categories

Table 4. *Cont.*

Title	Year	Method	Analysis	Main Takeaway
A Comparative Environmental Assessment of Heat Pumps and Gas Boilers towards a Circular Economy in the UK [12].	2021	Modelling/LCA	HP LCA	HP is better in emission but worse in other EI categories
Circular economy priorities for photovoltaics in the energy transition [61].	2022	Modelling	Module CE variables	The long life of modules is concluded as the best alternative to reduce virgin material demands under a PV modules model with CE variables
PV in the circular economy, a dynamic framework analysing technology evolution and reliability impacts [62].	2022	Modelling	Module CE variables	Present open-source tool to model CE variables of modules
A critical review of the circular economy for lithium-ion batteries and photovoltaic modules-status, challenges, and opportunities [63].	2022	Literature review	Module and LIB CE variables	An extensive literature review of modules and LIBs shows a focus on recycling. Other CE strategies are commented
When to replace products with which (circular) strategy? An optimization approach and lifespan indicator [64].	2021	Modelling/LCA	Heating CE variables	Long lifetimes are not always better, calculated for HPs with CE variables and alternatives

4. Discussion

4.1. Qualitative Method Limitations

The advantages of the proposed method are that qualitative trends are represented numerically, therefore reducing human bias and allowing for automated and repeatable processes.

Limitations of this approach are that the tool only considers papers and ignores "institutional reports" or theses. Many of these research papers have closed access; therefore, there may be different trends that are not represented by this approach. Similarly, the selected paper sources are general and standardised, therefore suited for comparing different technologies and analysis modes with the same procedure. Nevertheless, it is possible that specific paper sources with a heavy focus and better results are available by sacrificing standardization. This bias can be solved by increasing and generalising the obtention of papers (more sources of paper, closed access).

Furthermore, processing errors such as failures to download, extract, and store caused by internet connection, website construction, PDF structure, or type of content may lead to a reduction in candidates or content. An example is that only text is processed, and images are ignored. Using the proper wording is fundamental, as word similarities are not recognised; plural-singular or synonyms must be actively and manually considered on the list of indicators. The search was performed by trying representative words and discarding low-frequency ones as they did not make an impact. When a concept does not show a unique clear indicator, groups are presented. To compare concept groups, the same quantity of indicators is needed to have a fair comparison between groups. Searches are conducted over "text find", not "word is in", which means that text is analysed as a whole, not as a list of words; therefore, using acronyms could lead to many false positives. Alternatively, more advanced word search options (capitalization, acronyms, adjective detection, position of word in text) are possible and would make for richer future development of the tool.

Additionally, some searches present a low quantity of matches; therefore, not much can be concluded from them. Finally, even if a topic is addressed, this does not indicate if a positive or negative evaluation is made of it.

4.2. Quantitative Method Limitations

Available values in product datasheets face varied challenges, such as a lack of standardisation of values, names, and units, as well as future estimations for operation and degradation. Additionally, values of environmental impacts and ageing are arduous to measure and, therefore, hard to control. On the other hand, historical and statistical descriptions are difficult to perform due to quick technological evolution and the long time needed to assess life cycle results.

As recognised by other sources, data gathering is a challenging process where the use of proprietary software and databases is needed, industrial secrecy is present, and details are not always explicitly given, such as system boundaries, type and quantity of materials and parts, material loss during production, origin country and transportation of raw material, among others.

4.3. Qualitative Trends and Gaps

While analysing sustainability, some research topics receive more focus than others. This is represented by the number of papers or the appearance of specific words in those papers. PV inverters are highly neglected, representing 6% of the matches, mainly with reliability analysis playing a role, while interest in End-of-life is only substantially present in PV modules. Meanwhile, LIBs research is more abundant at 33%, as the automotive industry has even more restrictive conditions than PV use; therefore, there is some "research intersection". Sustainability analysis focuses primarily on energy and emissions, as the most frequent concepts are words such as 'climate change', 'energy', 'emission', or 'co2'. Proportions change depending on analysis mode and wording, but energy topics represented 40% of matches in LCA original concepts, 79% in LCA extended concepts, and 50% for manufacturing under the aforementioned conditions. When material concepts are present, they are mostly related to 'recycling' and 'waste', with matches representing 28% of CE original concepts, 38% of CE extended concepts, and 62% for EoL under the mentioned conditions. Specific modes to apply Circular Economy beyond recycling have infrequent appearances. Exact materials and modes of failure can appear, especially for LIBs and PV panels, but not as often as energy concepts.

Generally, incentives in the CE still need to be clarified. A tendency towards energy and emissions is understandable as these can be more or less directly correlated with costs. Even if less clear, the importance of raw materials, recycling, and waste still appears, as they can also be linked to costs. Other variables appear more diluted in cost estimation, as middle CE strategies as maintain, prolong, reuse, redistribute, refurbish, remanufacture. A disadvantage for them is also that they are much more component/model dependent, reducing scalability. Reinterpreting less-treated topics as advantages (e.g., cost saved) would more clearly present their importance for a person not immersed in the topic.

4.4. Quantitative Trends and Gaps

Previous trends are similarly present in quantitative variables. To model life cycle impacts from a circular economy perspective, production and operation factors are easier to find than EoL or repairability variables. Again, PV modules and LIBs have more information available, but values are presented in a general manner as there are many possible technologies and operation modes. Usually, 'standard' average values are used, while papers can present a broader range according to technological, economic, or user conditions. Most values are obtained from statistical reports, as technical sheets only offer variables for initial system dimensioning and generalised degradation. Better estimation of life impacts could be achieved with the standardisation of product datasheets, environmental indexes, and units. Acknowledging this, wide ranges for some variables are also found, where differences between minimum and maximum are significant for the lifetime of modules with 4.3 times, 2.7 times for inverter, 2.5 for batteries, in failure rates of 5600 for modules, and 16.4 times for inverters. The exact effect of these uncertainties on environmental impacts and costs should be calculated for each use case, but final results must include sensitivities and uncertainty ranges to account for them.

From the manufacturer's side, different types of datasheets and datasets are available but with limited access and standardisation. Encouraging open access to component reports with agreed variables, names, and units would be imperative. When industrial secrets are at risk, the material composition could be replaced by impact categories as presented in environmental declarations, but again, under a single standard. Operational measurements to identify degradation and failure should be published as raw data, even if this is not for the complete lifecycle. This would allow us to assess the effects of other variables not considered when focusing on a single point of study. With the increased application of these energy systems in the public sector, installation in public buildings could serve as an example of data openness. Claims made by manufacturers should be tested under these operational conditions.

5. Conclusions

Circular Economy is a strategy that fights climate change and E-waste simultaneously, as it offers strategies to increase the efficiency of used material at the design, use, and End-of-Life stages both for producers and users. From an automated analysis of electrical energy components in a 'near Zero Energy Building' combined with circular strategies, the key observations are:

Automated review:

- Allows for reduction in time, bias, and error through automation. Anyhow, manual validation and calibration are still needed;
- Literature sources themselves present biases through access type and scope;
- The presented tool and methodology do not replace the expert's knowledge but allow for a more efficient way to find specific information.

Qualitative concepts:

- High representativity of Lithium batteries is present due to automotive research;
- Relegation PV inverters;
- Favouritism for CO_2 and Global Warming Potential and energy consumption over other environmental impacts;
- Favouritism for recycling over other Circular Economy strategies;
- Recognizing all possible combinations of components and strategies allows for easier identification of priorities, but incentives for each still need to be studied case by case;
- Expressing less treated CE strategies and components in terms of gains or losses avoided can make these studies more attractive.

Quantitative values:

- Lack of many key indicators (e.g., repairability or recycling energy) or average values used;
- Wide range degradation models for LIBs, but no equivalents for other components;

- The potential for recycling given by technology and material differs significantly from onsite real rates. Developing markets for this will correlate with increased waste as old components phase out;
- For available values, wide ranges and different units are found depending on the technology of each component. The difference between min and max could reach up to 5600 times in the worst case;
- Due to quick technological evolution and the time needed for statistical measurements, available values are old or estimated;
- Climatic conditions or user patterns are not always stated for calculations;
- Standardization of metrics and units delivered with products is a must to ensure comparability.

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sustainability

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Review

Framing Concepts of Agriculture 5.0 via Bipartite Analysis

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Abstract: Cultural diversity often complicates the understanding of sustainability, sometimes making its concepts seem vague. This issue is particularly evident in food systems, which rely on both renewable and nonrenewable resources and drive significant environmental changes. The widespread impacts of climate change, aggravated by the overuse of natural resources, have highlighted the urgency of balancing food production with environmental preservation. Society faces a pivotal challenge: ensuring that food systems produce ample, accessible, and nutritious food while also reducing their carbon footprint and protecting ecosystems. Agriculture 5.0, an innovative approach, combines digital advancements with sustainability principles. This study reviews current knowledge on digital agriculture, analyzing scientific data through an undirected bipartite network that links journals and author keywords from articles retrieved from Clarivate Web of Science. The main goal is to outline a framework that integrates various sustainability concepts, emphasizing both well-studied (economic) and underexplored (socioenvironmental) aspects of Agriculture 5.0. This framework categorizes sustainability concepts into material (tangible) and immaterial (intangible) values based on their supporting or influencing roles within the agriculture domain, as documented in the scientific literature.

Keywords: digital; food; nexus; ontology; socioenvironmental; sustainability

1. Introduction

Significant advancements in computer science are driving digital innovations across industries [1], including agriculture [2]. Digital and Precision Agriculture (Agriculture 4.0) relies on technologies like proximal (near target) sensors, which include electrical resistors, isotope detectors, and various types of spectrometers (e.g., visible, near-infrared, and laser-based) [3–5]. These sensors are also mounted on aerial and satellite platforms, equipped with multispectral and hyperspectral capabilities, LIDAR (Light Detection and Ranging), and radar systems like SAR (Synthetic Aperture Radar), which capture data in the microwave spectrum.

Modern monitoring devices produce vast amounts of data across a range of spatial (millimeters to meters) and temporal (fractions of a second to weeks) scales [6]. Looking forward, if these agricultural datasets can be integrated through interoperable big data platforms [7], allowing diverse datasets to be easily shared and analyzed across different platforms, they could enable complex analytics and data-driven decision-making through advanced machine learning (ML) and artificial intelligence (AI) techniques [8,9]. Future big data systems may rely on platforms-as-a-service (PaaS), edge computing, quantum computing, and fast 5G and 6G networks [10].

Technology-driven approaches like Industry 4.0 have become accessible to small- and medium-sized enterprises [11]. More recently, the European Commission introduced Industry 5.0, a concept that focuses on value-oriented economies that serve humanity within planetary boundaries [12]. This shift parallels the move from Agriculture 4.0 to Agriculture 5.0, which aims to address socioenvironmental issues. While Agriculture 4.0 primarily emphasizes data collection [2,13,14], Agriculture 5.0 seeks to use digital transformation to enhance decision-making, data precision, and accessibility, especially for smallholder farmers [9]. By supporting social equity and digital inclusion, Agriculture 5.0 can help produce and distribute culturally relevant, carbon-neutral food across diverse cultural, economic, and political landscapes [15,16].

Agriculture 4.0 already encompasses numerous developments, particularly for pre-harvest and harvest stages, which are applied to both annual crops (e.g., wheat, soybeans, corn) and perennial crops (e.g., fruit and timber). Innovations include improved water management, soil fertility and carbon adjustment, pest control, and advanced monitoring for plant and livestock health [17]. For annual crops, techniques like vegetation health and climate indices from satellite imagery allow AI-based assessments of plant health and targeted fertilizer or amendment application [18–22]. For perennial crops, digital tools like mechanized pruning and automated pest control enhance productivity [23–28]. In precision livestock farming [29], sensor technologies track grazing patterns and animal health [30–33], while UAV imagery estimates forage biomass [34] and increases the productivity [35,36] of integrated crop–livestock systems (ICLS) or crop–livestock–forestry systems (ICLFS) [37,38]. These systems, where crops and livestock are managed together for mutual benefits [39–41], foster sustainable interactions, thus protecting native ecosystems and supporting conservation [42,43].

Connecting Agriculture 4.0 with ICLS, ICLFS, and agroforestry systems (AFS) could also repurpose degraded lands into productive landscapes [44–46]. However, challenges in infrastructure, aging farmer populations, data accessibility, and market dynamics limit adoption [47–49]. Addressing these challenges is essential [15], especially as climate change and resource depletion threaten the sustainability of food systems [9,12,24]. Moving from Agriculture 4.0 to 5.0 calls for a comprehensive approach where data collection, analytics, and decision-making are integrated to enhance sustainable agriculture. This shift can support food security, environmental preservation, and economic prosperity in a world with complex socioenvironmental demands [16].

This study aims to identify knowledge gaps in Agriculture 5.0 through an analysis of current scientific data, using a bipartite network to associate scientific journals with key(words) terms from articles in the Clarivate Web of Science database. By establishing a framework that connects concepts within Agriculture 5.0, this study highlights the balance between technology and socioenvironmental sustainability, offering a value-oriented framework [12,50] to guide future research and policy toward sustainable agriculture [8,14,16,51].

2. Materials and Methods

2.1. Data Source

Data for this analysis were collected from publications indexed in the Clarivate Web of Science (WoS) database. The search, conducted on 29 January 2024, included all fields for publications from 1945 to 2023, following PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines for systematic reviews [52]. PRISMA is a standard method for systematic reviews used to track article extraction. Figure 1 provides the PRISMA diagram, with each step of the systematic process.

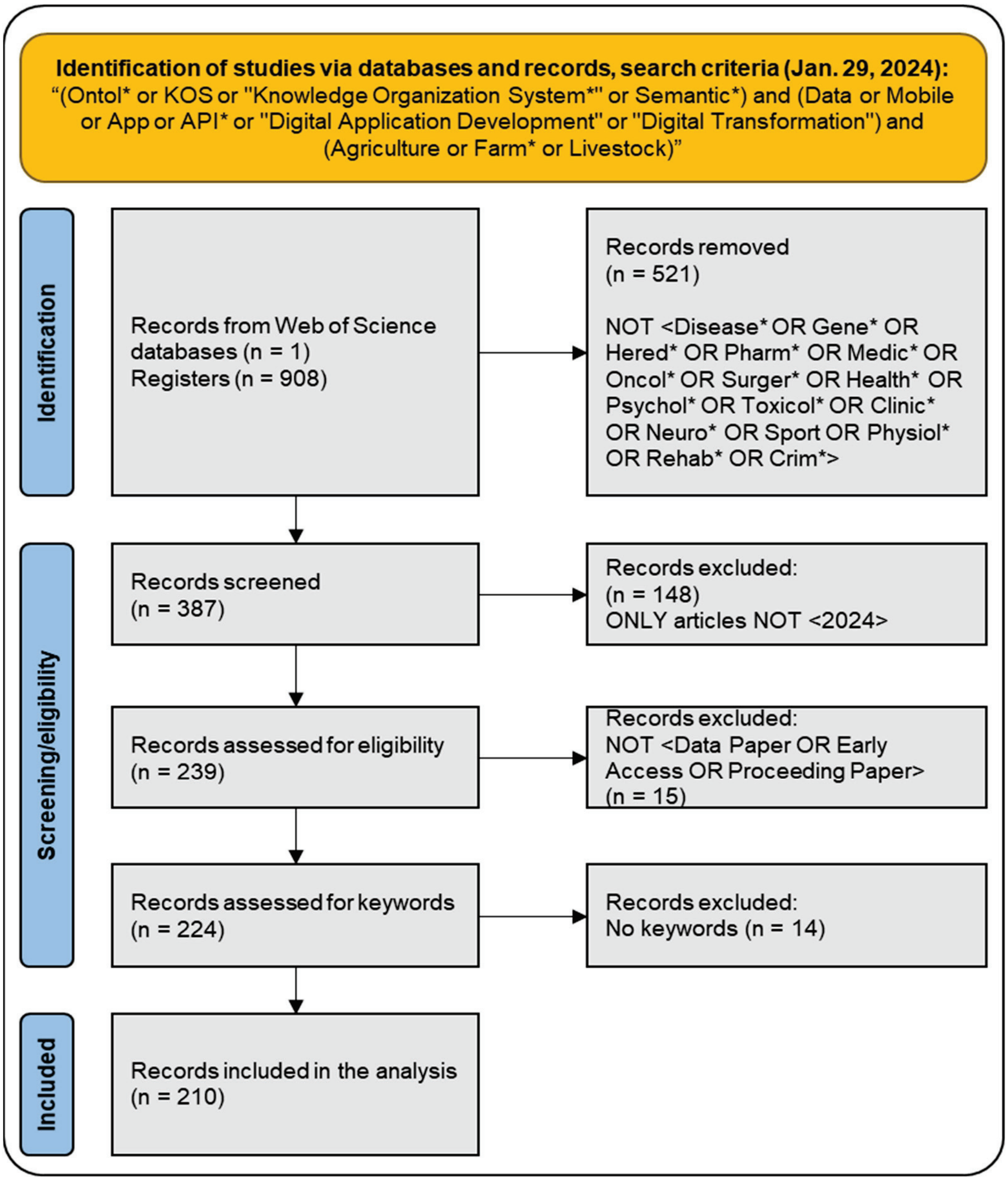

Figure 1. PRISMA methodology for extracting relevant articles in Web of Science. The symbol * stands for any additional character.

2.2. Identification

The search terms were grouped into three major categories to capture relevant publications, as follows:

- (Class 1) Knowledge organization—keywords focused on terms associated with knowledge structuring, including ontologies and semantic networks [53,54] designed to structure and classify knowledge;
- (Class 2) Terms representing digital advancements, such as "API" (Application Programming Interface) [51];
- (Class 3) Agriculture—terms related to land use, plant, and livestock systems.

"Agriculture 5.0" was not included in the search to avoid bias, as it is an emerging term.

The search strategy combined relevant terms from each class, using a logical string, as follows:

- Class 1—<Ontol* or KOS or "Knowledge Organization System*" or Semantic*>;

- Class 2—<Data or Mobile or App or API* or "Digital Application Development" or "Digital Transformation">;
- Class 3—<Agriculture or Farm* or Livestock>.

2.3. Screening, Eligibility and Inclusion

To minimize irrelevant results, especially from health-related studies, terms associated with medical or psychological fields were excluded. Only full articles were included, and publications from 2024 or those without author keywords were omitted. Keywords Plus, an algorithm-generated keyword list from WoS, was excluded to prioritize author-provided terms. Following these criteria, 210 articles were extracted, including 120 journal titles and their author keywords for the bibliometric network analysis.

2.4. Network Analysis

A bibliometric analysis was conducted on a bipartite network—called a keyword–journal network—consisting of two node types, keywords (D) and journals (J), linked by published articles [55]. The network's properties include:

- Bipartite—nodes link only between keywords and journals, not between nodes within the same set;
- Undirected—relationships lack hierarchy and reflect shared topics;
- Weighted—edges include information on how frequently a keyword appears in a particular journal.

Bipartite network analysis is a powerful tool for constructing the semantic framework of Agriculture 5.0, as it effectively captures relationships between two distinct entities—keywords (concepts) and journals. This method ensures an unbiased exploration of sustainability dimensions, integrating technological and socioenvironmental aspects critical to Agriculture 5.0. The separation of domains in bipartite analysis prevents artificial links within the same set (e.g., between keywords or journals), focusing instead on how journals act as conduits for specific concepts. By mapping keywords to journals, the analysis identifies high-degree nodes or "superhubs", which represent influential journals disseminating critical knowledge. These superhubs highlight dominant themes, while less frequent themes may be associated with little-explored concepts.

The keywords underwent a disambiguation process to group similar terms (e.g., CNN and Convolutional Neural Network). After this process, the final set included 823 keywords. The bipartite keyword–journal network was represented as a graph $G = (D, J, E)$, where D and J are the keyword and journal sets, and E is the weighted edges. Starting from matrix A ($n \times m$), where n represents keywords and m represents journals, the adjacency matrix M of G is defined as follows [55]:

$$M = \begin{bmatrix} 0 & A \\ A^T & 0 \end{bmatrix}$$

Graphical representations of the network were generated using Gephi (v. 0.10, https://gephi.org/, accessed on 1 October 2024), applying algorithms to calculate centrality measures (i.e., the importance of a node) betweenness, weighted node degree (k_w), and clustering. Node clustering was achieved with default settings of "Modularity Class" [56], and bipartite analysis was carried out with default settings of the plugin "MultiMode Network Projection" (https://github.com/jaroslav-kuchar/Multimode-Networks, accessed on 1 October 2024). The combined method allows for deriving two new networks, as depicted in the intuitive example below (Figure 2). When decomposed into two new networks, the thickness of an edge between two nodes of the same set reflects the frequency at which they were previously connected with nodes of the other set.

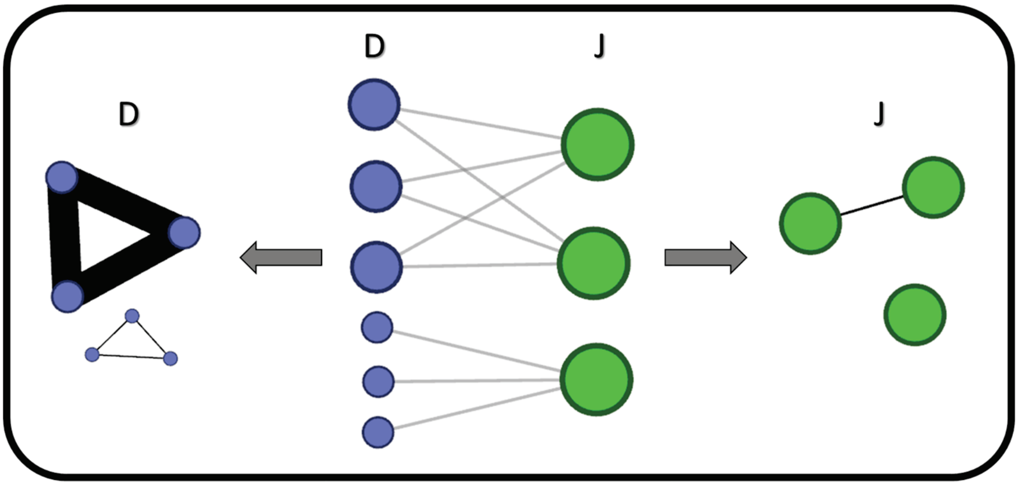

Figure 2. Schematic representation of a bipartite analysis of two sets of nodes, *D* (purple) and *J* (green).

The network's modularity class algorithm can reveal clusters of keywords (*D* set) with high and low centrality. Keywords with high centrality are generally related to economic applications of digital transformation, while keywords with low centrality suggest emerging socioenvironmental topics within Agriculture 5.0.

As a result, key sustainability concepts were extracted from the bipartite keyword–journal network analysis and integrated into a dynamic social framework [15,57]. To minimize epistemological biases, this value-oriented framework for Agriculture 5.0 was constructed by linking multidimensional sustainability concepts through semantic relationships found in the scientific literature. By structuring the framework as a directed network, it highlights both the direction and strength of connections among sustainability concepts, with nodes and node labels sized by weighted in-degree and out-degree centralities [58]. These weighted centrality measures offer insights into each concept's role, with in-degree centrality indicating support and out-degree centrality representing influence within the network. This nexus-driven approach helps reveal how different sustainability concepts interact and contribute to the overall framework.

3. Results

Figure 3 illustrates the growth in citations of the selected articles, showing an increase from 2004 to 2023. These 210 articles were cited a total of 3,466 times. The exponential trend in citations, with an annual increase rate of around 30%, highlights growing interest in the field. The uptick in citations starting around 2004 aligns with the release of the Millennium Ecosystem Assessment report (http://www.millenniumassessment.org, accessed on 1 October 2024), which examined the impacts of ecosystem changes on human well-being and recommended policies to promote the sustainable use of ecosystems.

Figure 4 displays two visualizations of the undirected bipartite network, which consists of 943 nodes and 1129 edges, linking 120 journal nodes (in blue) and 823 keyword nodes (in red). The larger network layout uses the Force Atlas 2 algorithm with settings to reduce hub formation and prevent node overlap. The inset image uses the Circle Pack Layout algorithm, grouping nodes based on hierarchy (node type and centralities), followed by the Expansion algorithm. Due to the network's bipartite structure, direct links between two keywords or two journals do not exist; rather, connections between keywords and journals occur indirectly via shared topics.

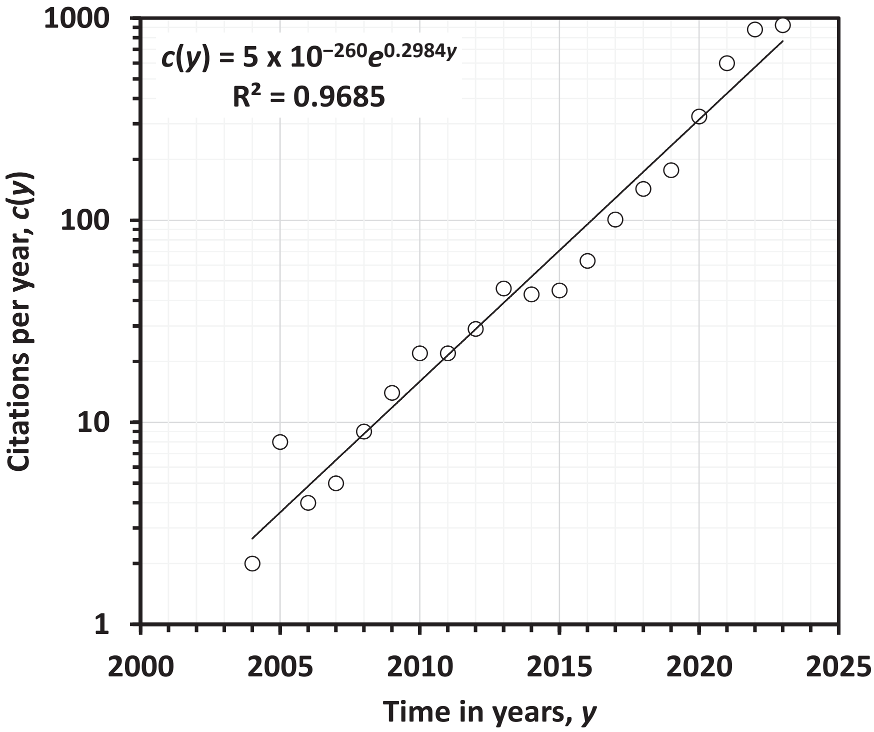

Figure 3. Exponential growth rate (~30%.y^{-1}) of scientific interest in included articles.

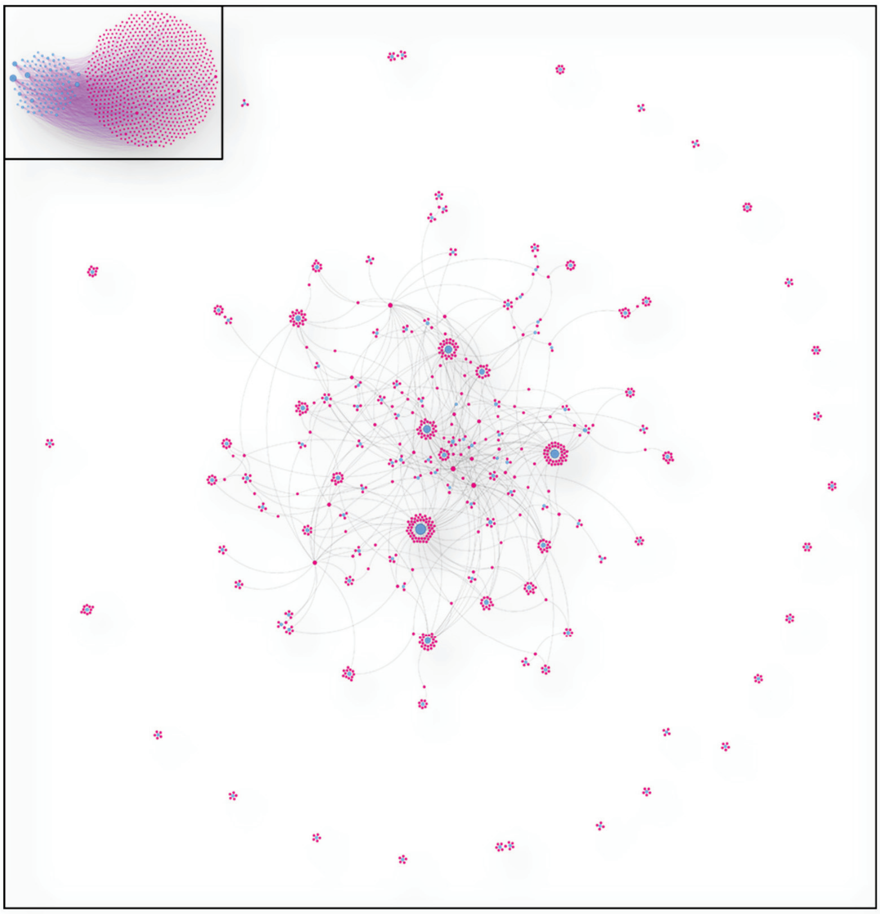

Figure 4. Two representations of the same undirected bipartite graph with 943 nodes and 1129 links between journals (in blue, 120 nodes) and keywords (in red, 823 nodes). The size of the nodes is proportional to the weighted degree centrality.

Figure 5 presents the distribution of weighted degrees (k_w) in the network. This distribution likely (out of two points, in black) follows a power-law decay, indicating that a few high-degree nodes serve as central hubs in the network, while many others have lower connectivity [59]. Five key journal nodes (superhubs) were identified with a high k_w value (>64), attracting keywords across articles and establishing them as prominent sources in this knowledge domain [60].

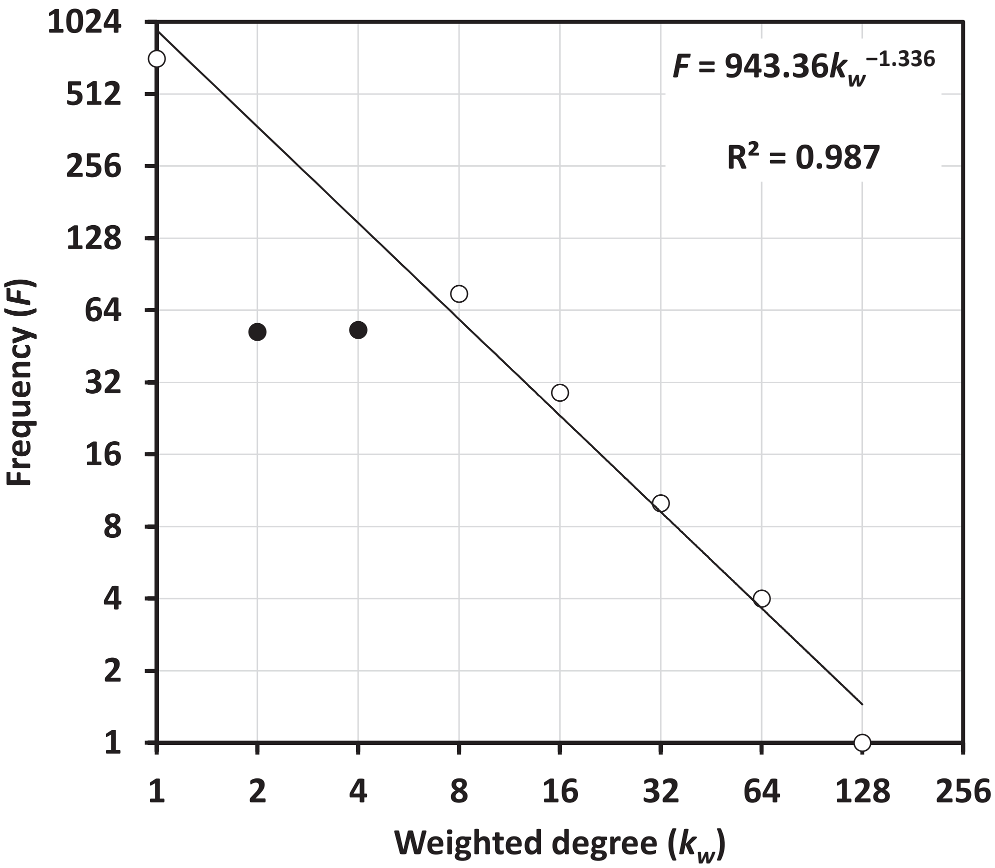

Figure 5. Log-binned (2^n for n = 0, 1, . . ., 7) node degree distribution of the keyword–journal network extracted from the 210 selected publications. Dark circles were disregarded in the statistical regression.

3.1. Identification and Selection of Conceptual Assets from the Bipartite Keyword–Journal Network

Figure A1 (Appendix A) presents the one-partition J set of journals, while the one-partition D set of keywords are shown in Figures 6 and 7. The undirected network graph of keywords comprises 823 nodes linked by 11,259 edges, with an average k_w of 28.5. Clustering analysis (26 clusters) identifies high k_w clusters, particularly a large blue cluster in Figure 6. This cluster represents keywords with high connectivity, typically linked to the economic and technological aspects of sustainability. The lower k_w clusters, shown in detail in Figure 7, contain keywords associated with emerging socioenvironmental aspects of Agriculture 5.0.

Conceptual assets were selected based on these clusters, representing both high-centrality (economic) and low-centrality (socioenvironmental) sustainability dimensions (Table 1). These assets were screened for their roles within Agriculture 5.0, allowing for a preliminary framework that differentiates between technological (economic) and socioenvironmental concepts. The screening was deliberately limited to manage complexity and focus on key insights. This pragmatic approach allowed for a clear and actionable preliminary framework while leaving room for future refinement and expansion as the field evolves.

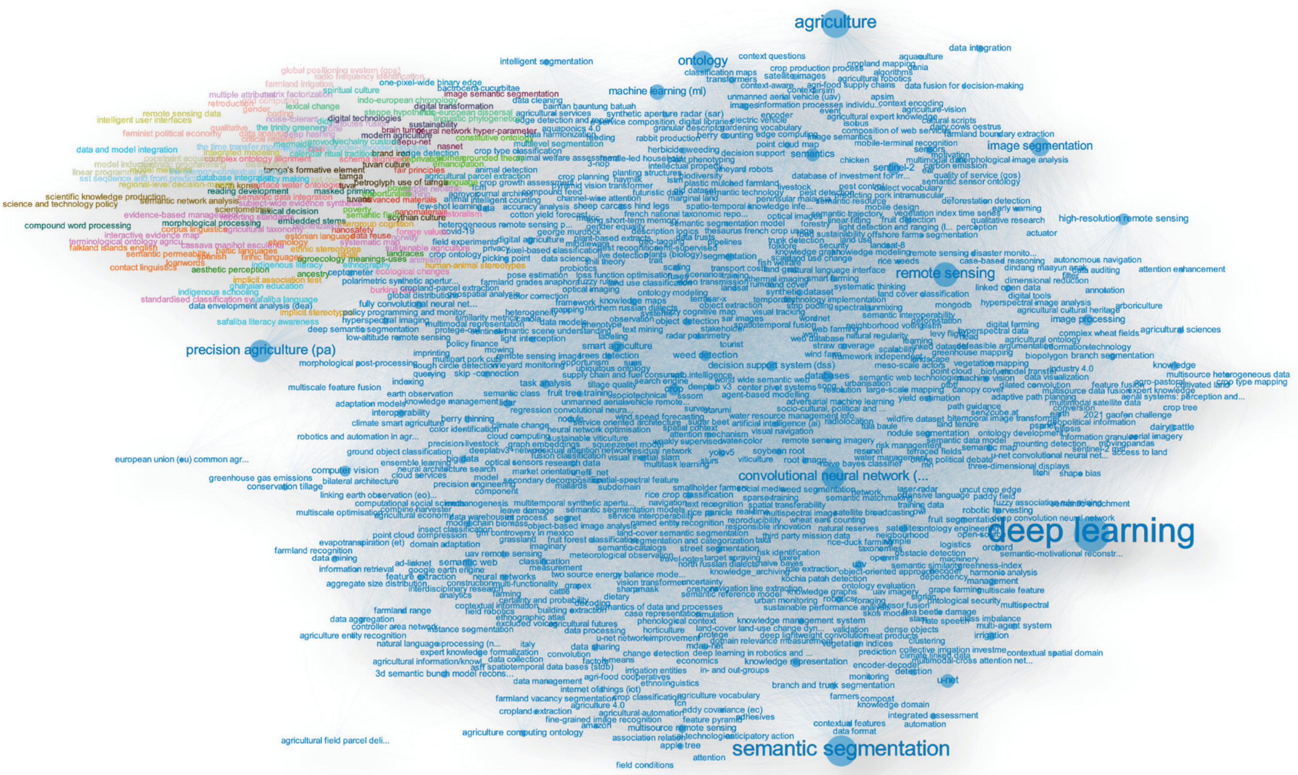

Figure 6. Keywords semantics from the bipartite analysis. The size of the nodes (labels) is proportional to the weighted degree (betweeness) centrality.

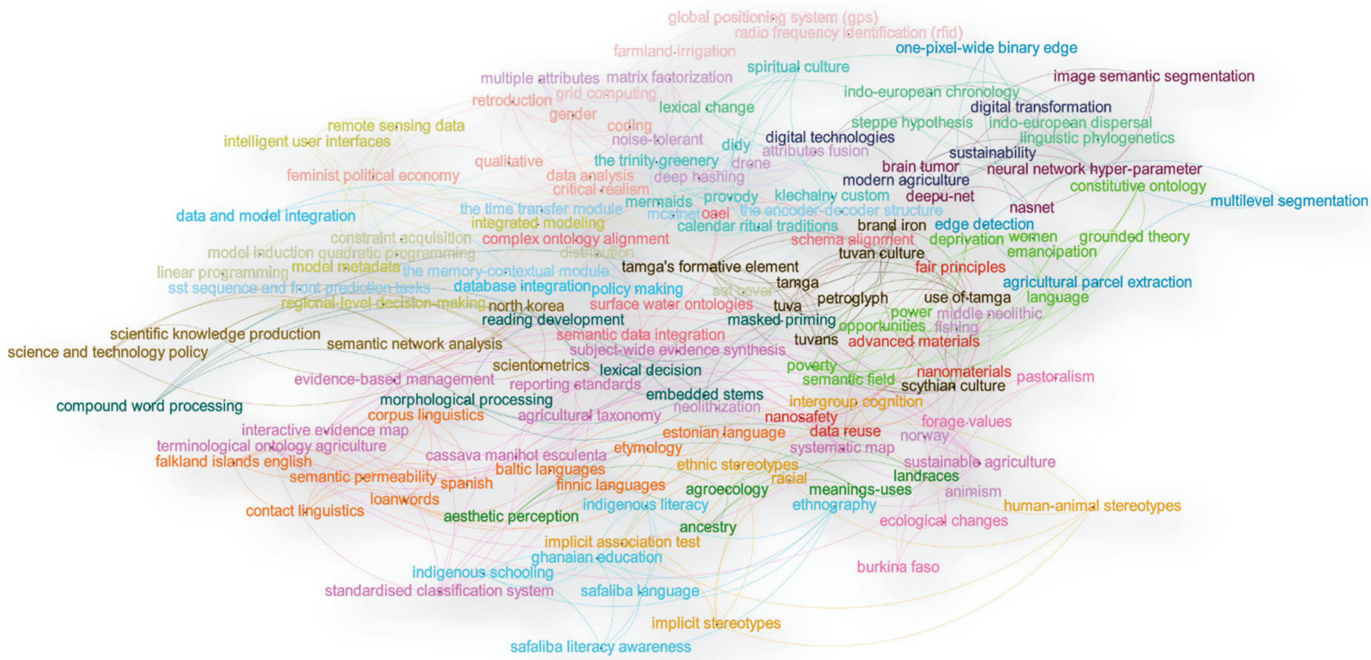

Figure 7. Details of subsets of underexplored keywords among journals.

Table 1. Major conceptual preliminary assets extracted and selected from k_w extreme values (very small and very large) obtained in 26 clusters. Most relevant concepts for screening preliminary assets are highlighted in bold (n = 31). * k_w values between $167 \leq k_w \leq 430$ shown in parenthesis. ** all k_w values shown in parenthesis.

Cluster	k_w	Extracted Concepts	Selected Assets	Selected References
0	1–430 *	**deep learning** (430), **semantic segmentation** (377), **agriculture** (344), **remote sensing** (301), convolutional neural network (cnn) (278), **precision agriculture** (272), ontology (267), **image segmentation** (233), **machine learning** (187), u-net (167)	7	n = 95 publications, see Table A1
1	2	**data** and model integration, **database integration**, **policy making**	3	58 citations [61]
2	3	agricultural parcel extraction, edge detection, multilevel segmentation, one-pixel-wide binary edge	0	-
3	3	farmland irrigation, global positioning system (gps), grid computing, radio frequency identification (rfid)	0	-
4	3	burkina faso, ecological changes, forage values, pastoralism	0	-
5	3	digital technologies, digital transformation, modern agriculture, **sustainability**	1	2 citations [62]; uncited [63]
6	4	mcstnet, sst sequence and front prediction tasks, the encoder-decoder structure, the memory-contextual module, the time transfer module	0	-
7	4	complex ontology alignment, oaei, schema alignment, semantic data integration, surface water ontologies	0	-
8	4	north korea, **science and technology policy**, **scientific knowledge production**, scientometrics, **semantic network analysis**	3	7 citations [64]
9	4	integrated modeling, intelligent user interfaces, model **metadata**, regional-level **decision-making**, remote sensing data	2	12 citations [65]
10	4	FAIR principles, nanomaterials, **data reuse**, nanosafety, advanced materials	1	3 citations [66]
11	4	animism, fishing, middle neolithic, neolithization, norway	0	-
12	4	indo-european chronology, indo-european dispersal, lexical change, linguistic phylogenetics, steppe hypothesis	0	-
13	4	brain tumor, deep u-net, image semantic segmentation, nasnet, neural network hyper-parameter	0	unrelated
14	4	aesthetic perception, agroecology, **ancestry**, landraces, meanings-use	1	uncited [67]
15	5	attributes fusion, deep hashing, drone, matrix factorization, multiple attributes, noise-tolerant	0	-
16	5	compound word processing, embedded stems, lexical decision, masked priming, morphological processing, reading development	0	-
17	5	constraint acquisition, distribution, linear programming, model induction, quadratic programming, set cover	0	-
18	5	ethnography, ghanaian education, indigenous literacy, indigenous schooling, safaliba language, safaliba literacy awareness	0	-
19	5	**ethnic** stereotypes, human-animal stereotypes, implicit association test, implicit stereotypes, intergroup cognition, **racial**	2	1 citation [68]
20	6	coding, **critical realism**, **data analysis**, feminist political economy, **gender**, qualitative, retroduction	3	492 citations [53]
21	6	calendar **ritual traditions**, didy, klechalny custom, mermaids, provody, spiritual culture, the trinity greenery	1	uncited [69]
22	8	brand iron, petroglyph, scythian **culture**, tamga, tamga's formative element, tuva, tuvan culture, tuvans, use of tamga	1	1 citation [70]
23	9	agricultural taxonomy, cassava manihot esculenta, evidence-based management, interactive evidence map, reporting **standards**, standardised classification system, subject-wide evidence synthesis, sustainable agriculture, systematic map, terminological ontology agriculture	1	uncited [71]
24	4–9 **	**poverty** (9), deprivation (5), **language** (5), **power** (5), **women** (5), semantic field (5), constitutive ontology (4), grounded theory (4), **emancipation** (4), opportunities (4)	5	2 citations [72]; 18 citations [73]
25	5–9 **	loanwords (9), contact linguistics (5), corpus linguistics (5), falkland islands english (5), semantic permeability (5), spanish (5), finnic languages (4), baltic languages (4), estonian language (4), etymology (4)	0	-
Total	-	-	31	-

3.2. *Economy: The Core Dimension of Sustainability in Agriculture 4.0*

The main assets from Cluster 0 in Table 1—"deep learning", "semantic segmentation", "agriculture", "remote sensing", "precision agriculture", "image segmentation", and "machine learning"—were mapped into nine conceptual assets that define the economic dimension of sustainability. These assets represent applications within Agriculture

4.0 that support technological advancements, enabling better monitoring, analysis, and management practices. The conceptual applications include the following:

- Detection—identifying or detecting beneficial or harmful elements within agricultural systems;
- Forecasting—using historical data to predict future trends or events;
- Framework—providing guidelines for building useful systems or solutions;
- Mapping—assigning geographic locations to specific land cover or crop classes;
- Modeling—creating representations that accurately reflect reality;
- Monitoring—recording and analyzing data over time to track processes;
- Policy—developing principles, rules, or guidelines to achieve long-term sustainability goals;
- Privacy—ensuring individuals' control over how their data are collected and utilized;
- Security—providing reliability, safety, and trust in the use of technological applications.

The association between these conceptual assets and their applications in digital agriculture was established through a detailed review of 95 articles that referenced these keywords (Table A1 in Appendix A). Figure A2 shows the mapping between these keywords and the nine economic sustainability concepts, illustrating a "domain-to-range" relationship, i.e., linking specific keywords to broader conceptual categories.

Figure 8 illustrates the new bipartite analysis of the mapping in Figure A2, resulting in a semantic network of economic sustainability concepts in Agriculture 4.0, where edges represent the connections between these economic conceptual assets. Node and label sizes reflect weighted degree and betweenness centrality distributions, respectively, to emphasize the role of each concept within the network.

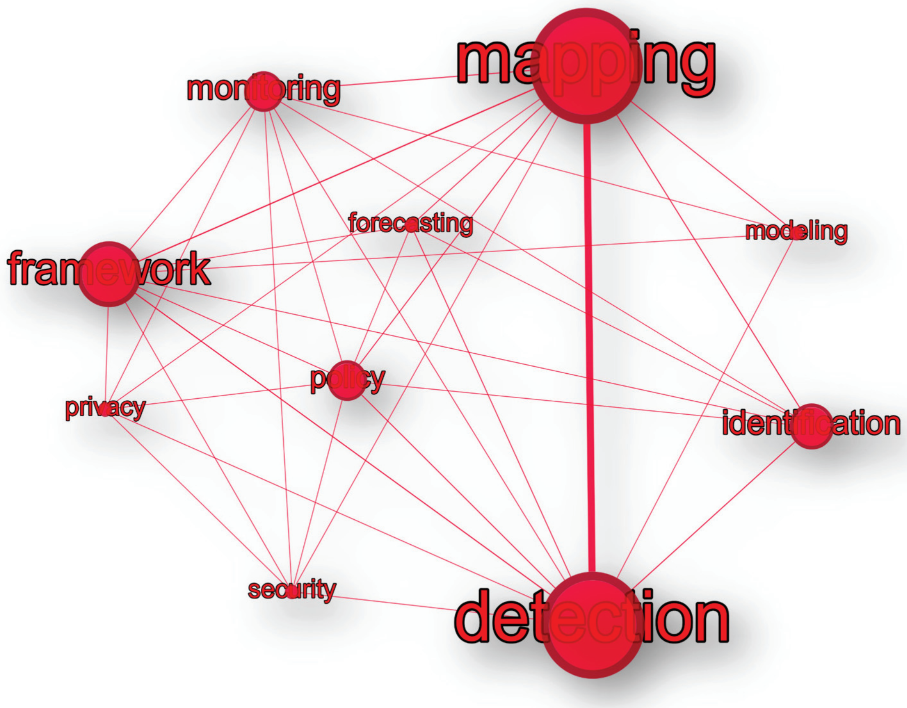

Figure 8. Network of conceptual assets of the Economic (technological application) dimension of Sustainability obtained from the bipartite analysis between "economic keywords" and the nine conceptual assets of the economic dimension of sustainability. The bipartite network is shown in Figure A2. The size of the nodes (labels) is proportional to the weighted degree (betweeness) centrality.

In Figure 8, notable connections exist between mapping (through remote and proximal sensing) and detection (primarily via proximal sensing). These connections are key for identifying specific targets and monitoring environmental changes. Modeling (through simulations of real-world processes) and forecasting (predicting future conditions) are linked as well, supporting the construction of comprehensive frameworks for sustainable knowledge organization. Together, these processes inform policy creation, guiding both public and private sectors in addressing sustainability challenges.

While the importance of privacy and data security is recognized, these concepts are among the lower-centrality nodes in the network. This suggests that while essential, they are less frequently addressed within the current technological applications of Agriculture 4.0, possibly indicating an area for future development as digital agriculture evolves.

4. Discussion

4.1. Socioenvironmental Dimensions of Sustainability in Agriculture 5.0

There is an urgent need for interdisciplinary research and synthesis focused on food and farming systems. Such efforts should produce culturally, economically, and politically appropriate insights to ensure that food production and distribution address both economic and ecological sustainability [15]. For example, cluster 1 (Table 1) highlights keywords like "data", "model integration" and "policy making" [61], which underscore the importance of agriculture databases structured with semantic relationships, based on meaning or conceptual similarity, and shared ontologies. Such structured datasets enable more reliable data-driven decision-making.

The broader concept of "sustainability" (cluster 5) emerges from recent literature emphasizing strategic planning as essential for integrating diverse data required for sustainable agriculture [62,63]. Additionally, studies reveal the critical role of smallholder farmers, especially women-led agricultural enterprises [63], in aligning with the Sustainable Development Goals (SDGs) set by the United Nations [43].

Other clusters reveal emerging socioenvironmental aspects of Agriculture 5.0. For instance, cluster 8 highlights the use of semantic networks to enhance scientific and technological policymaking (cluster 8). Similarly, cluster 9 emphasizes structured data and metadata for process-based modeling, particularly in addressing human impacts on natural resources [46]. Cluster 10 highlights data reuse, advocating for governance frameworks based on F.A.I.R. (Findable, Accessible, Interoperable, and Reusable) principles to support socioenvironmental goals [66].

Notably, cluster 14 introduces the concept of ancestry and its relationship to cultural aspects in agriculture [65], while cluster 19 adds concepts like ethnic and racial diversity [67]. These socio-cultural elements impact how communities perceive agricultural practices and the adoption of sustainable technologies [74,75]. Clusters 21 and 22 address cultural traditions and rituals [69,70], with examples like cereal production practices from Ukrainian folklore and the symbolic role of animal marking in nomadic societies [76]. Together, these findings highlight the challenges of integrating diverse cultural contexts into standardized (cluster 23) frameworks for sustainable agriculture [71].

Finally, clusters 20 [53] and 24 [72,73] address themes of gender, poverty, power, and emancipation, reinforcing the importance of fair representation and inclusivity in sustainable development. The inclusion of these socioenvironmental dimensions underscores the need for a value-oriented framework in Agriculture 5.0 that recognizes both material (tangible) and immaterial (intangible) factors influencing sustainability [53,72,73,77].

4.2. Developing a Framework of Conceptual Assets of Agriculture 5.0

The digital transformation of agriculture relies on precision and digital technologies that, if adapted to local contexts, can generate high-value agricultural products and address socioenvironmental challenges [10]. From a critical realism perspective [53], this framework needs to be rooted in the recognition that reality (ontology) cannot be simplified into our knowledge of it (epistemology). Critical realism promotes an ontological approach that minimizes biases [53], acknowledging the inherent complexity of sustainability concepts [57].

In Agriculture 5.0, the conceptual assets framework distinguishes between material and immaterial values [12]. Achieving sustainability in agriculture involves addressing not only tangible (economic) needs, but also intangible (socioenvironmental) factors such as user values, cultural connections, and well-being [77]. Prototyping the framework as a directed network allows the relationships between these assets to be structured according to weighted in-degree (support) and out-degree (influence) centralities, clarifying each asset's role within the network [58].

Table 2 summarizes the value-oriented conceptual assets for Agriculture 5.0, categorizing them based on support and influence roles derived from scientific literature. The framework highlights that certain assets—such as technology, sustainability, and policy-making—are pivotal, influencing other dimensions and guiding sustainable agricultural practices.

Table 2. Value-oriented conceptual assets in Agriculture 5.0 and their semantics based on the nexus of "support" and "influence" in the scientific literature. The symbol * indicates incremental material assets.

Conceptual Asset	Value	Support (In-Degree)	Influence (Out-Degree)
Agriculture	Material	Ethnic, Language, Policy-making [78–85]	Language, Ritual tradition, Technology [79,80,82,83,85–89] and see also Table A1
Ancestry	Immaterial	-	Culture, Ethnic [74]
Certification *	Material	Sustainability [90]	Information [90]
Culture	Immaterial	Ancestry, Language, Ritual tradition [74,83,85,91,92]	Agriculture, Language, Ritual tradition [74,83,85]
Data	Material	Metadata standard, Privacy, Security, Technology [93–96]	Information [94]
Decision making	Material	Knowledge [97]	Policy making [90,98,99]
Detection	Material	Technology (Table A1)	Technology (Table A1)
Education	Material	Policy making [99]	Ethic, Sustainability [100,101]
Equality	Immaterial	Gender, Race, Ethic [102–104]	Sustainability [105]
Ethic	Immaterial	Education [106]	Equality [100,101]
Ethnic	Immaterial	Ancestry, Race, Ritual tradition [74,83,91,92]	Agriculture [78,90]
Vocabulary *	Material	Language [107]	Metadata standard [108]
Forecasting	Material	Modeling (Table A1)	Knowledge (Table A1)
Gender	Immaterial	-	Equality [109]
Identification	Material	Technology (Table A1)	Technology (Table A1)
Information	Material	Data (Table A1)	Modeling (Table A1)
Intellectual property *	Material	Technology (Table A1)	Technology (Table A1)
Knowledge	Material	Forecasting (Table A1)	Decision making (Table A1)
Language	Immaterial	Agriculture, Culture, Vocabulary [74,83,91,92,107]	Agriculture [79,80,85]
Mapping	Material	Technology (Table A1)	Technology (Table A1)
Metadata standard	Material	Language, Privacy, Security, Technology [95,110–112]	Data [93], Information technology—Metadata registries (MDR)—Part 6: Registration
Modeling	Material	Information (Table A1)	Forecasting (Table A1)
Monitoring	Material	Technology (Table A1)	Technology (Table A1)
Privacy	Immaterial	Sustainability [113]	Data, Metadata standard [93,95,112,113]
Policy making	Material	Decision making [98]	Agriculture, Education, Sustainability, Technology [84,99,114]
Race	Immaterial	-	Equality, Ethnic [102–104]
Ritual tradition	Immaterial	Agriculture [87,89,92]	Culture, Ethnic [74]
Security	Immaterial	Sustainability [113]	Data, Metadata standard [93,95,112]
Sustainability	Immaterial	Education, Equality, Policy making [84,99,105,109]	Agriculture [84]
Technology	Material	Detection, Identification, Intellectual property, Mapping, Monitoring, Policy making [114] and Table A1	Data, Detection, Identification, Intellectual property, Mapping, Monitoring, Metadata standard [112]

In the corresponding graph of the directed network (Figure 9), agriculture influences elements like language, ritual traditions, and technology, while being supported by policy [99] and ethnic factors [78]. For instance, agricultural practices are often shaped by traditional languages and rituals, as seen in the deep-rooted agricultural societies of South America [79] and East Asia [83], where language and agricultural knowledge evolved together [68,74,91,93]. This co-evolution has been observed in civilizations across different regions, underscoring the historical and cultural (heritage) significance of agricultural practices [75,85,87–89].

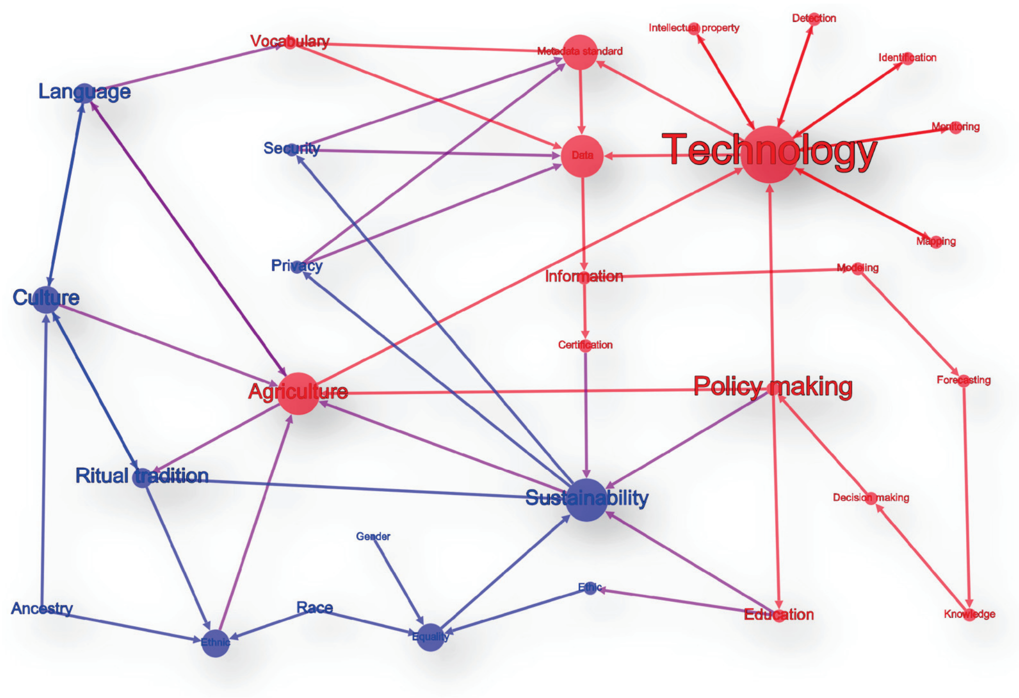

Figure 9. Framework of material (red) and immaterial (blue) conceptual assets in Agriculture 5.0 as a directed network graph of weighted support (larger labels) and influence (larger nodes).

Assets such as privacy and security [93–96] are fundamental in the current technological landscape, ensuring that agricultural data collection respects individual rights [81,82]. As digital transformation progresses, concepts like metadata standards [108] and controlled vocabularies [95,107,110–112] will play crucial roles in structuring agricultural data for certification [90], while education [100,101] will remain vital for cultivating knowledge on sustainable practices [102–104,113].

The framework's integration of diverse conceptual assets reflects the complex interplay of economic, social, and environmental elements essential to Agriculture 5.0 [78,84,97]. A value-oriented approach to Agriculture 5.0 will need to consider not only the practical applications of technology, but also the broader socioenvironmental contexts in which agricultural practices occur [98,99,105,114], particularly in the context of climate change [10,13] and smallholders [90].

Table 3 summarizes the main roles of conceptual assets in Agriculture 5.0. "Technology" stands out as the primary supporter and influencer of other key assets. Overall, major supporters include Technology, Sustainability, Agriculture, Data, Metadata Standards, Culture, Equality, and Ethnic Diversity. In contrast, major influencers are Technology, Policy Making, Sustainability, Agriculture, Culture, Language, and Ritual Tradition. These findings suggest that focusing research and development on these key assets could significantly advance a value-oriented Agriculture 5.0.

Table 3. Weighted influencer (supported by) and supporter roles of Agriculture 5.0 conceptual assets.

Conceptual Asset	Value	Influence	Support
Technology	Material	7	7
Sustainability	Immaterial	5	3
Agriculture	Material	5	3
Data	Material	5	1
Metadata standard	Material	4	1
Culture	Immaterial	3	3
Equality	Immaterial	3	1
Ethnic	Immaterial	3	1
Language	Immaterial	2	3
Ritual tradition	Immaterial	2	3
Ethic	Immaterial	1	1
Vocabulary	Material	1	2
Privacy	Immaterial	1	2
Security	Immaterial	1	2
Decision making	Material	1	1
Detection	Material	1	1
Education	Material	1	2
Forecasting	Material	1	1
Identification	Material	1	1
Information	Material	1	2
Knowledge	Material	1	1
Mapping	Material	1	1
Modeling	Material	1	1
Monitoring	Material	1	1
Policy making	Material	1	4
Intellectual property	Material	1	1
Certification	Material	1	1
Ancestry (Heritage)	Immaterial	0	2
Gender	Immaterial	0	1
Race	Immaterial	0	2

5. Conclusions

The digital transformation in agriculture holds potential not only for economic gains, but also for fostering sustainable practices. Agriculture 5.0 aims to go beyond data collection to develop actionable insights that provide real-world benefits. However, there is concern that concentrating large volumes of data and analytical power within a few entities could exacerbate inequalities, excluding those with fewer resources and increasing the risk of environmental degradation unless well-regulated.

In this study, a bipartite network analysis was applied to identify core sustainability concepts in Agriculture 5.0, proposing a framework that connects economic and socioenvironmental dimensions. This preliminary framework underscores the need for a balanced approach that integrates both technological advancements and socioenvironmental priorities. The shift from Agriculture 4.0 to 5.0 represents a promising pathway to enhance food security and environmental stewardship, aligning with the United Nations Sustainable Development Goals (SDGs).

While technological advancements will continue to drive progress, establishing shared standards, semantic agreements, and protocols for socioenvironmental data is likely essential for long-term sustainability. This study's approach provides an initial structure for such a framework, though further development and formalization, possibly through Web Semantics or ontology-based methods, will be needed to refine it.

Author Contributions: Conceptualization, I.B.; methodology, I.B.; data curation, I.B.; writing—original draft preparation, I.B.; writing—review and editing, I.B., J.G.A.B., É.L.B. and R.Y.I.; project administration, S.M.F.S.M. and L.A.S.R.; funding acquisition, S.M.F.S.M. and J.G.A.B. All authors have read and agreed to the published version of the manuscript.

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

Appendix A

Figure A1 displays the J set of journals, as structured in Figure 2. Generated with the Force Atlas 2 layout, the graph includes 120 journal nodes connected by 977 edges, with an average weighted degree (k_w) of 23.9. Node sizes and labels represent k_w and betweenness centralities, while colors indicate 26 clusters derived from the modularity class algorithm. Within the largest blue cluster in Figure 5, key "superhub" journals are highlighted, including Computers and Electronics in Agriculture (k_w = 180), IEEE Access (k_w = 143), Remote Sensing (k_w = 102), IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing (k_w = 97), and IEEE Sensors Journal (k_w = 88).

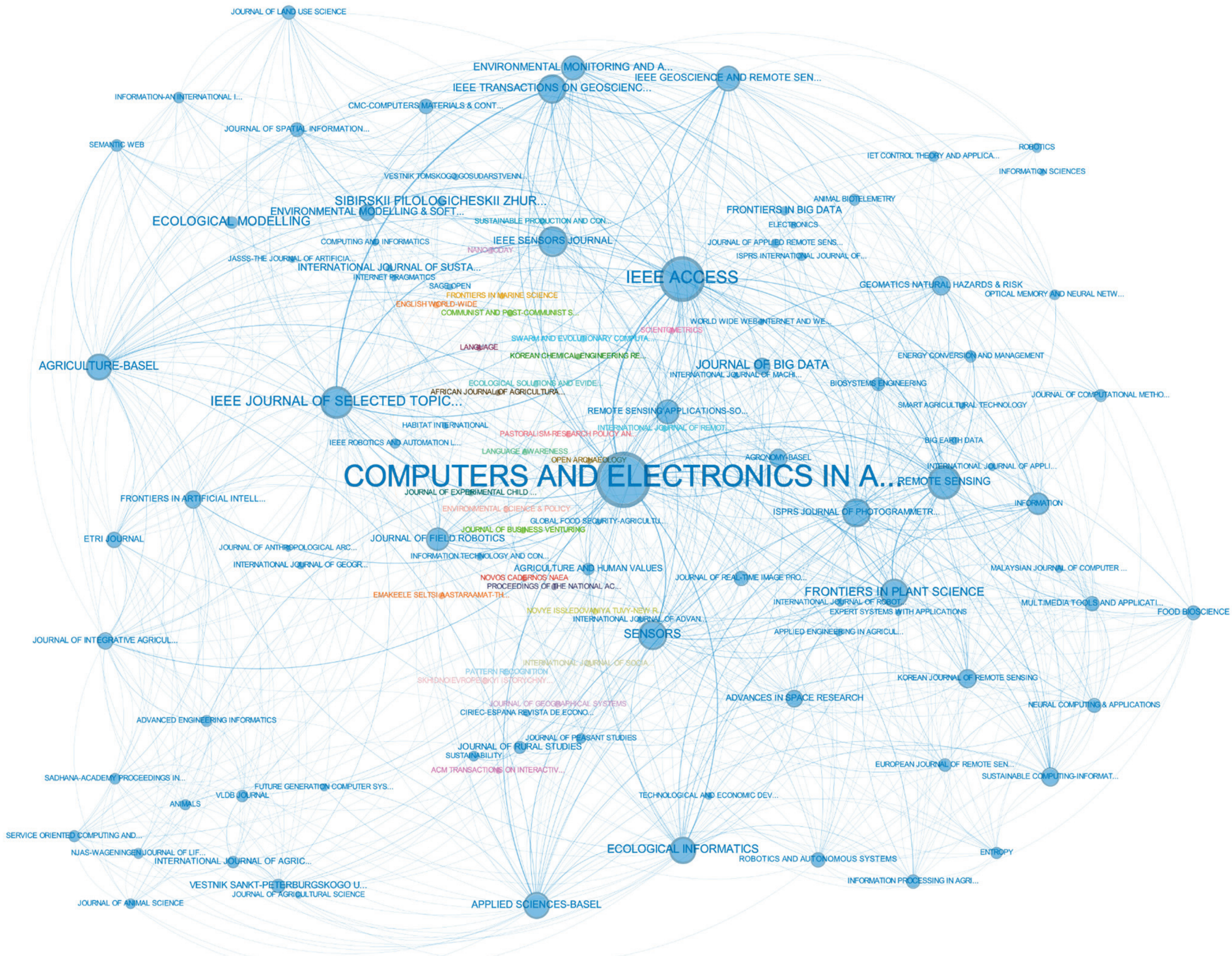

Figure A1. *J* (journals) set from the bipartite analysis of the keyword–journal network.

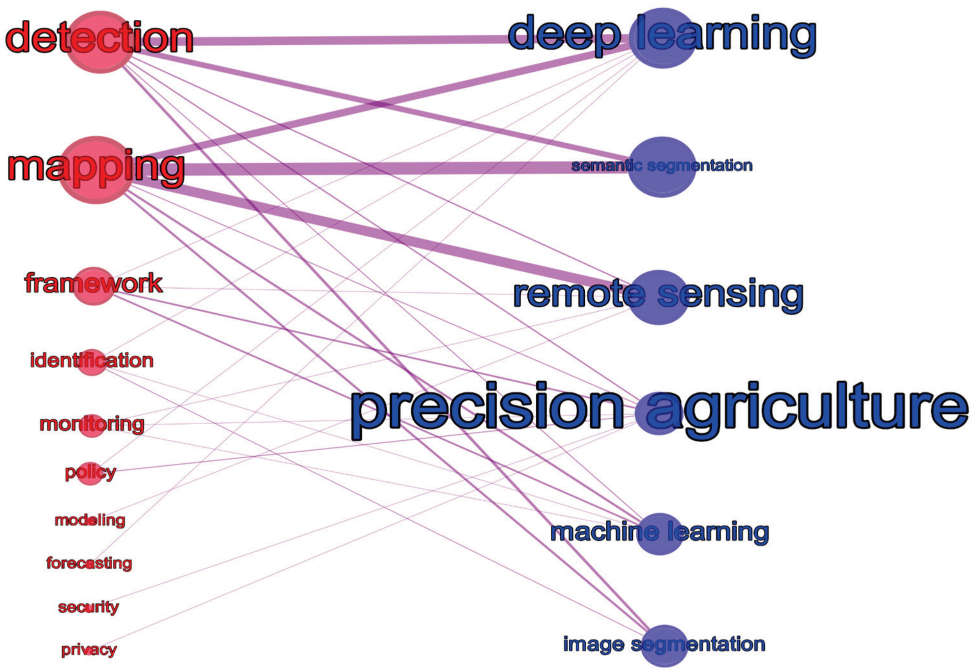

Figure A2. Bipartite undirected network between superhub keywords (blue) and application categories (red). The size of nodes (labels) is proportional to weighted degree (betweeness) centrality, while the thickness of the edges is related to ties strength.

Table A1. Bipartite correspondence between applications and superhub keywords in 95 publications from cluster 0 (Table 1).

Application	Publication DOI	Publication Year	Superhub Keywords
detection	10.1007/s11554-023-01264-0	2023	deep learning, precision agriculture
detection	10.1016/j.compag.2020.105302	2020	deep learning
detection	10.1016/j.compag.2020.105504	2020	deep learning
detection	10.1016/j.compag.2020.105760	2020	precision agriculture
detection	10.1016/j.compag.2023.107881	2023	deep learning, semantic segmentation
detection	10.1016/j.inpa.2022.05.002	2023	semantic segmentation
detection	10.1016/j.isprsjprs.2023.09.021	2023	deep learning
detection	10.1016/j.rsase.2021.100627	2021	deep learning, semantic segmentation
detection	10.1016/j.suscom.2022.100759	2022	deep learning, semantic segmentation
detection	10.1109/ACCESS.2020.2991354	2020	deep learning, semantic segmentation, precision agriculture
detection	10.1109/ACCESS.2021.3108003	2021	deep learning, semantic segmentation
detection	10.1109/JSEN.2021.3071290	2021	deep learning, semantic segmentation, image segmentation
detection	10.1109/LRA.2023.3320018	2023	image segmentation
detection	10.3390/agriculture11020131	2021	deep learning
detection	10.3390/rs15215124	2023	deep learning, semantic segmentation, remote sensing
detection	10.3390/s20185292	2020	deep learning, remote sensing, image segmentation
detection	10.3390/s21144801	2021	semantic segmentation
detection	10.3390/s22197131	2022	image segmentation
detection	10.7780/kjrs.2021.37.3.1	2021	deep learning, semantic segmentation
detection & identification	10.1016/j.compag.2021.106451	2021	image segmentation, machine learning
detection & identification	10.1109/TGRS.2021.3093041	2022	deep learning, image segmentation

Table A1. *Cont.*

Application	Publication DOI	Publication Year	Superhub Keywords
detection & identification	10.3390/rs14092004	2022	deep learning
detection & mapping	10.1016/j.biosystemseng.2020.05.022	2020	deep learning
detection & mapping	10.1016/j.compag.2019.03.028	2019	machine learning
detection & mapping	10.1016/j.compag.2023.108217	2023	semantic segmentation
detection & mapping	10.1016/j.isprsjprs.2021.08.024	2021	deep learning, semantic segmentation
detection & mapping	10.1080/19475705.2023.2196370	2023	deep learning, semantic segmentation, remote sensing
detection & mapping	10.1109/LRA.2019.2901987	2019	deep learning
forecasting	10.1016/j.enconman.2020.113098	2020	deep learning
framework	10.1109/ACCESS.2021.3128178	2021	deep learning
framework	10.1109/ACCESS.2022.3198099	2022	precision agriculture
framework	10.1109/JSTARS.2021.3139155	2022	precision agriculture
framework	10.1117/1.JRS.16.024519	2022	machine learning
framework	10.1145/3453172	2021	remote sensing
framework	10.1186/s40537-023-00729-0	2023	precision agriculture, machine learning
framework	10.21638/11701/spbu10.2022.206	2022	precision agriculture
framework	10.32604/cmc.2023.030924	2023	machine learning
framework	10.3389/fdata.2020.00012	2020	machine learning
mapping	10.1007/s00521-020-05561-8	2023	semantic segmentation
mapping	10.1007/s10661-022-10848-5	2023	deep learning, semantic segmentation, remote sensing, image segmentation
mapping	10.1007/s11042-022-12141-6	2022	semantic segmentation
mapping	10.1016/j.asr.2023.05.007	2023	semantic segmentation, remote sensing
mapping	10.1016/j.compag.2020.105277	2020	deep learning
mapping	10.1016/j.compag.2020.105369	2020	semantic segmentation, remote sensing
mapping	10.1016/j.compag.2021.106482	2021	deep learning, semantic segmentation
mapping	10.1016/j.compag.2022.106731	2022	deep learning, remote sensing
mapping	10.1016/j.compag.2023.107754	2023	semantic segmentation
mapping	10.1016/j.ecoinf.2023.102078	2023	deep learning, semantic segmentation
mapping	10.1016/j.fbio.2023.102848	2023	semantic segmentation, machine learning
mapping	10.1016/j.isprsjprs.2021.09.005	2021	deep learning, semantic segmentation
mapping	10.1016/j.isprsjprs.2022.01.007	2022	deep learning, semantic segmentation
mapping	10.1016/j.isprsjprs.2023.06.014	2023	semantic segmentation
mapping	10.1016/j.jag.2021.102511	2021	remote sensing
mapping	10.1016/j.robot.2023.104581	2024	semantic segmentation, precision agriculture
mapping	10.1080/03066150.2012.665890	2012	remote sensing
mapping	10.1080/22797254.2023.2181874	2023	semantic segmentation
mapping	10.1109/ACCESS.2019.2913442	2019	semantic segmentation
mapping	10.1109/ACCESS.2021.3069882	2021	remote sensing
mapping	10.1109/JSTARS.2021.3132259	2022	image segmentation, machine learning
mapping	10.1109/JSTARS.2022.3208185	2022	remote sensing, image segmentation
mapping	10.1109/JSTARS.2023.3301158	2023	remote sensing
mapping	10.1109/LGRS.2020.3037976	2022	semantic segmentation, image segmentation
mapping	10.2316/J.2022.206-0730	2022	remote sensing
mapping	10.3389/fpls.2022.1030595	2023	semantic segmentation, remote sensing
mapping	10.3389/fpls.2023.1196634	2023	deep learning, remote sensing
mapping	10.3389/fpls.2023.1228590	2023	deep learning, semantic segmentation, remote sensing
mapping	10.3390/agriculture12111894	2022	machine learning
mapping	10.3390/app12168234	2022	deep learning, semantic segmentation, remote sensing
mapping	10.3390/e23040435	2021	semantic segmentation
mapping	10.3390/ijgi12020081	2023	machine learning
mapping	10.3390/info12060230	2021	deep learning, semantic segmentation, remote sensing

Table A1. *Cont.*

Application	Publication DOI	Publication Year	Superhub Keywords
mapping	10.3390/info13050259	2022	deep learning
mapping	10.3390/rs11172008	2019	semantic segmentation, remote sensing
mapping	10.3390/rs12132159	2020	deep learning
mapping	10.3390/rs13040612	2021	deep learning, semantic segmentation
mapping	10.3390/rs13214370	2021	semantic segmentation, remote sensing
mapping	10.3390/rs13214411	2021	remote sensing
mapping	10.3390/rs14092157	2022	remote sensing
mapping	10.3390/rs14194694	2022	semantic segmentation
mapping	10.3390/rs15102500	2023	deep learning, semantic segmentation, remote sensing
mapping	10.3390/sens12060230	2020	deep learning
mapping	10.9713/kcer.2019.57.2.274	2019	semantic segmentation
mapping & detection	10.1109/TGRS.2020.3029841	2021	image segmentation
mapping & detection	10.3390/agronomy13030635	2023	deep learning, remote sensing
mapping & detection	10.1002/rob.21877	2020	semantic segmentation, precision agriculture
mapping & detection	10.1109/ACCESS.2023.3308909	2023	semantic segmentation, remote sensing, machine learning
mapping & modeling	10.1080/1747423X.2021.1879296	2021	remote sensing
modeling	10.3390/rs12030342	2020	remote sensing
monitoring	10.1186/s40317-021-00248-w	2021	machine learning
monitoring	10.3390/rs15184403	2023	remote sensing
monitoring	10.3390/s20205768	2020	precision agriculture
policy	10.1016/j.jrurstud.2020.10.040	2022	precision agriculture
policy	10.1016/j.jrurstud.2020.10.040	2020	precision agriculture
policy	10.3233/JCM-226522	2023	deep learning
privacy & security	10.3390/su151310264	2023	precision agriculture

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