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Special Issue Reprint

Innovative Approaches toward Healthy and Sustainable Environment

Air, Water, Food, and Waste Treatment

Edited by
Shervin Hashemi

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Innovative Approaches toward Healthy and Sustainable Environment: Air, Water, Food, and Waste Treatment

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Guest Editor

Shervin Hashemi

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Guest Editor
Shervin Hashemi
Institute for Environmental
Research
Yonsei University College
of Medicine
Seoul
Korea, South

Editorial Office
MDPI AG
Grosspeteranlage 5
4052 Basel, Switzerland

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About the Editor

Shervin Hashemi

Dr. Shervin Hashemi holds concurrent positions as a senior researcher at the Institute for Environmental Research at the Yonsei University College of Medicine in Seoul, Republic of Korea, and as an honorary research associate at the Durban University of Technology, Faculty of Management Sciences, in South Africa. His primary research focus is water and sanitation provision in remote areas. Dr. Hashemi's innovative resource-circulated sanitation system garnered recognition through the *Leaving No One Behind Innovation Award 2019* and the *Energy Globe Republic of Korea National Award 2019*. Additionally, he developed the *Sanitation Sustainability Index* to assess the technical, economic, and social sustainability of local sanitation systems. Since 2017, Dr. Hashemi has been an active member of the Management Committee of the International Water Association (IWA) Resource-Oriented Sanitation Specialist Group. In 2021, he received a nomination for the *IWA Global Water Award*, which acknowledges individuals who have made significant contributions to the judicious use of water globally through innovative leadership and practices.

Preface

Pursuing a healthy and sustainable future has become increasingly critical in the era of unprecedented environmental challenges. Our planet faces numerous interconnected issues, including air pollution, water scarcity, food insecurity, and waste management. At this juncture, exploring innovative solutions to address these pressing concerns, along with establishing a foundation for a more sustainable future, is imperative.

The "*Innovative Approaches toward Healthy and Sustainable Environment: Air, Water, Food, and Waste Treatment*" is a Special Issue of the journal *Sustainability* that presents a comprehensive examination of cutting-edge strategies and technologies aimed at addressing some of the most urgent environmental problems of our time. This volume aggregates the expertise of leading researchers, practitioners, and scholars from across the globe, offering a multidisciplinary perspective on the complex challenges we face and the innovative solutions that are being developed to overcome them.

This Special Issue comprises one editorial, thirteen research articles, and two reviews. Readers will encounter four fundamental pillars of environmental sustainability: clean water supplies, the rethinking of food systems, innovative waste treatment, and the water–energy–food–ecosystem nexus. Each section provides an in-depth analysis of current affairs, examining the root causes of environmental degradation and its far-reaching impacts on human health and ecosystems. Furthermore, this reprint showcases groundbreaking approaches and technologies that are revolutionizing our interactions with the environment and its protection.

From water treatment methods to sustainable agricultural practices and innovative waste recycling solutions, this volume presents a diverse array of tools and strategies with the potential for a cleaner, healthier, and more sustainable future. By highlighting empirical case studies and successful implementations, the authors aim to inform and motivate readers to actively participate in global efforts to preserve the planet for future generations.

As we navigate the complex landscape of environmental challenges, this book serves as both a guide and a call to action, encouraging readers to think critically, act decisively, and collaborate across disciplines and borders to forge a path toward sustainability. Whether one is a scientist, policymaker, entrepreneur, or concerned citizen, "*Innovative Approaches toward Healthy and Sustainable Environment: Air, Water, Food, and Waste Treatment*" offers valuable insights and practical solutions to help shape a more environmentally conscious future for all.

Shervin Hashemi
Guest Editor

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Editorial

Advancing Healthy and Sustainable Environmental Stewardship: Reimagining Strategies for Air, Water, Food, and Waste Management

Shervin Hashemi [1,2]

[1] Institute for Environmental Research, Yonsei University College of Medicine, 50-1 Yonsei-ro, Seodae-mun-gu, Seoul 03722, Republic of Korea; shervin@yuhs.ac
[2] Faculty of Management Science, Durban University of Technology, Durban 4000, South Africa

Given the pervasive impacts of global climate change and environmental degradation, there is an urgent need to develop innovative approaches to establish a trajectory towards a healthy and sustainable environment. The worldwide response to the COVID-19 pandemic has revealed significant vulnerabilities in critical environmental resource management [1]. While the significance of air, water, food, and waste management has long been recognized, the pandemic has underscored the fragility of the systems supporting these resources. Air pollution, contaminated water sources, food insecurity, and unsustainable waste management practices collectively contribute to a broader crisis in public health and environmental sustainability. In response to global challenges, nations and communities have acknowledged the need for innovative and comprehensive crisis resolution and reconstruction approaches.

The Earth is at a critical juncture with formidable challenges related to clean air, pure water, sustainable food systems, and efficient waste management [2–4]. In this context, it is imperative to adopt forward-looking solutions to address these issues and to facilitate a harmonious relationship with the environment. Consequently, the Special Issue entitled 'Innovative Approaches towards Healthy and Sustainable Environment: Air, Water, Food, and Waste Treatment' has been established. The Special Issue solicited papers exploring emerging innovative air, water, food, and waste management approaches. The aim was to elucidate how recent technological advancements, policy shifts, and community-driven solutions could be leveraged to create more sustainable and healthier environments. These approaches are particularly crucial in light of the ongoing environmental degradation and the increasing threats of climate change, population growth, and urbanization.

This Special Issue was initially structured into four sections, each addressing one of the key elements of environmental sustainability: air quality, water management, food security, and waste management. The papers accepted for each element aimed to discuss the challenges, innovative solutions being implemented, and potential of the solutions to contribute to long-term environmental sustainability.

Air pollution is a significant concern because it adversely affects human health and the environment. These issues are now being addressed through innovative technologies such as artificial intelligence (AI) and Internet of Things (IoT) applications, which have emerged as transformative solutions [5]. Smart sensors facilitate real-time air quality monitoring and provide critical information for the timely intervention of urban authorities. Recent initiatives, including urban greening strategies for vertical gardens and green roofs, have also demonstrated efficacy in enhancing air quality while promoting biodiversity [6]. These

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methods reduce pollutants and contribute to healthier urban environments conducive to community well-being.

Water contamination and scarcity pose significant risks to millions of people worldwide [7]. Advanced filtration systems utilizing nanotechnology are being developed to treat wastewater for potential reuse, thereby maximizing the utilization of available water resources. Rainwater harvesting systems and modular water treatment plants represent scalable solutions, particularly for underserved communities [8]. Traditional conservation practices, such as watershed restoration, complement technological advancements by providing sustainable approaches to ensure universal access to clean water.

The current food production systems exhibit unsustainable characteristics. With the intensive and potentially harmful pesticides in monocultures and land overexploitation, every aspect of the food chain requires urgent revision. This necessitates the implementation of landscape-scale criteria for soil health, crop diversification, and ethical animal husbandry. Agroecological methods such as permaculture and agroforestry enable farmers to enhance biodiversity, sequester carbon, and mitigate the effects of erratic weather patterns associated with climate change [9]. Emerging trends in urban agriculture and vertical farming are gaining prominence, facilitating localized food production, reducing transportation emissions, and providing fresh produce for urban populations [10].

Novel waste treatment methodologies are imperative as waste generation rates increase. The circular economy concept has garnered significant attention because it aims to reduce waste generation and maximize resource recovery through product and process redesign [11]. Anaerobic digestion and composting technologies enable the conversion of organic waste into valuable resources including energy- and nutrient-rich soil amendments. Furthermore, advancements in recycling technologies have facilitated the production of high-quality output from mixed materials. These approaches contribute to reducing the burden on landfills and promoting responsible consumption behaviors among consumers.

The submission deadline for the Special Issue was 30 June 2024. More than twenty manuscripts were submitted for publication as of this date. Among these submissions, 15 papers successfully passed the peer-review evaluation process and were published. An alphabetically ordered list of these accepted contributions is provided in the List of Contributions.

Although approaches to revolutionizing air quality were one of the primary topics of the Special Issue, the number of potential contributions in this field was significantly lower compared to other themes. This indicates that substantial progress must be made in studying air quality for environmental sustainability. Given increasing concerns over climate change, urbanization, and pollution, air quality affects the health of ecosystems and human populations [12]. Poor air quality contributes to environmental and public health issues, including respiratory diseases, cardiovascular conditions, and the deterioration of biodiversity [13].

Consequently, advancing the knowledge of air quality and exploring innovative solutions is important. In this regard, most potential submissions were insufficient to demonstrate the connection between current advanced technologies and their applicability for enhancing environmental sustainability. This gap highlights the need for more focused high-quality research that bridges technological advancements with practical solutions for improving air quality. It also underscores the importance of interdisciplinary collaboration in integrating engineering, environmental science, and policymaking efforts that directly impact sustainability practices.

Among the accepted papers, Contributions 2, 6, and 11 pertain to the 'Clean Water Supplies' theme. Contributions 5, 10, and 14 address topics related to the 'Rethinking Food Systems' theme. The 'Innovating Waste Treatment' section encompassed the largest contri-

butions, including Contributions 1, 3, 4, 7, 8, 9, and 13. The remaining contributions, 12 and 15, were classified under the 'Water–Energy–Food–Ecosystem (WEFE) Nexus' approach. Figure 1 illustrates the distribution of contributions across themes.

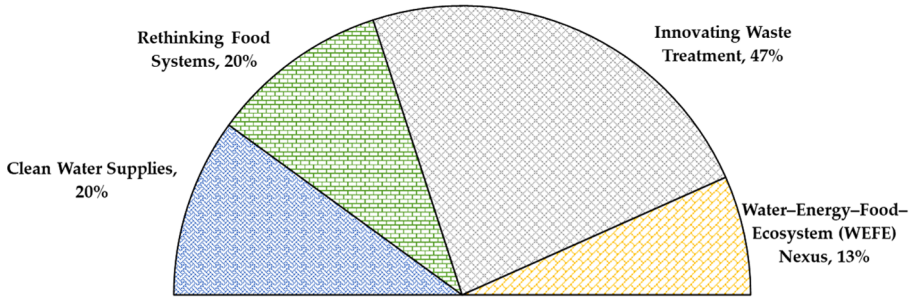


Figure 1. Distribution of contributions across themes in this Special Issue.

Pollution is recognized as one of the most significant environmental and public health threats worldwide. Contribution 2 highlights the growing concern over polluted habitats and the limitations of conventional treatment methods, which are often expensive and energy-intensive. This study proposes a bioremediation method that uses algae and bacteria. Focusing on the hydrocarbon- and heavy-metal-contaminated water of Al Asfar Lake in Saudi Arabia, Contribution 2 demonstrates that certain microalgal species, such as *Chlorella* sp. and *Geitlarianema* sp., exhibit the potential to remove harmful pollutants. This bioremediation method is effective, environmentally sustainable, and cost-efficient, and offers a potential solution for large-scale environmental pollution.

Access to clean and safe drinking water is critical in many rural areas, particularly in developing countries. Contribution 6 examines water quality in rural Kazakhstan, identifying significant chemical content variations depending on the drinking water source. The study reveals that many rural areas experience water contamination, with some villages reporting high cation and anion levels exceeding permissible limits. Notably, residents' perceptions of water quality were found to correlate with physical water characteristics such as taste, odor, and salinity. This underscores the importance of bridging the gap between scientific water quality assessments and public perception. Establishing robust communication channels between governing bodies and local populations can improve public health outcomes, engender confidence in water management infrastructure, and facilitate the widespread adoption of sustainable water utilization practices.

Discharging bilges and wastewater from ships to the sea is a significant environmental and public health concern. Contribution 11 investigates the carcinogenic and non-carcinogenic risks to human health associated with heavy metals in shipborne wastewater. Using data from Antalya Bay, this study employs the Monte Carlo simulation method to assess the risks from exposure to heavy metals such as copper, iron, chromium, and mercury. The results indicate that certain heavy metals, particularly nickel (Ni), arsenic (As), and chromium (Cr), pose a substantial carcinogenic risk to both swimmers and ship personnel. These findings underscore the urgency of addressing shipborne wastewater and bilge water contamination to protect human health, especially given that the carcinogenic risks in these discharges exceed the standards set by the World Health Organization (WHO). This study emphasizes the need for more stringent regulations and treatment methods to mitigate the health risks associated with maritime pollution.

Overall, Contributions 2, 6, and 11 highlight the critical role of pollution in environmental and public health issues in different contexts. While Contribution 2 proposes a novel bioremediation approach utilizing algae and bacteria, Contribution 6 draws attention to the complex relationship between water quality indicators and community perceptions,

which is vital for effective water resource management. Contribution 11 addresses the often-overlooked health risks from shipborne wastewater, a source of heavy metal contamination in marine environments. These studies underscore the need for innovative, interdisciplinary approaches to manage environmental pollution, improve water quality, and safeguard public health.

Climate change significantly threatens smallholder farmers' food security and livelihoods in regions such as Ethiopia. Contribution 5 examines how various climate change adaptation practices affect farmers' vulnerability to food insecurity in the Bench Maji Zone of southwest Ethiopia. This study highlights the importance of diverse adaptation strategies including crop management, soil and water conservation, and livelihood diversification. Using a multinomial endogenous treatment effect regression model to address selection bias and endogeneity, this study found that farmers employing multiple adaptation practices were less vulnerable to food insecurity. It recommends supporting farmers in implementing these practices through research, development, and collaboration between farmers, extension services, and researchers. This study emphasizes the crucial role of adaptation strategies in enhancing food security amid climate change.

As climate change intensifies global warming, energy-intensive industries such as cold-storage warehouses must adopt sustainable practices. Contribution 10 examined methods to increase warehouse sustainability by identifying effective practices and technologies through convergent interviews with experts. The resulting practices are organized hierarchically, from essential to best, including optimal refrigeration systems, advanced racking methods, and improved insulation. A key recommendation is to enhance reporting on both successful and unsuccessful implementation to promote wider industry adoption. This study underscores the importance of industry-specific diagnostic tools, such as convergent interviewing, to identify practical strategies for sustainable cold storage in Australia and highlights the need for innovation and communication in the refrigeration industry to mitigate environmental impact.

The global food system faces critical challenges such as increasing food availability, reducing food loss, and addressing food waste. Contribution 14 addressed the complex issues surrounding food consumption, loss, and waste by proposing an ontological framework that combines these three aspects into a cohesive systemic model. This framework offers a comprehensive approach to understanding and managing the intricacies of food systems globally. It accounts for 35,112 potential components related to food consumption, loss, and waste, providing a structured method to analyze and address the problem. The authors argue that the lack of a unified approach to these three factors leads to inefficient management strategies. By utilizing this ontological framework, decision-makers can identify gaps in current systems and develop strategies to bridge them, offering a more holistic solution for managing food systems. This approach provides a novel perspective on food management and can lead to more effective global strategies for addressing food-related challenges.

Overall, Contributions 5, 10, and 14 highlight the multifaceted nature of the environmental and food system challenges in the face of climate change. Contribution 5 demonstrates the importance of combining climate adaptation strategies to enhance smallholder farmers' resilience to food insecurity. Contribution 10 focuses on sustainable practices in the energy-intensive refrigeration industry, highlighting the potential for innovation in cold storage warehouses to reduce environmental impact. Contribution 14 offers a groundbreaking ontological framework for addressing the complex global issues of food consumption, loss, and waste. These studies reflect the growing need for integrated environmental and food management. Addressing climate impacts on agriculture, promoting sustainability in industries such as refrigeration, and holistically managing food systems are all critical for fostering resilience and ensuring long-term sustainability.

Environmental consciousness has prompted a re-evaluation of human waste management, particularly regarding human manure, as a potential resource rather than a liability. Contribution 1 investigates vermicomposting as a sustainable approach for nutrient recovery from human waste. This study examines microbial dynamics by comparing vermicomposting to conventional aerobic composting methods. These findings indicate that vermicomposting is more expeditious owing to the presence of earthworms, although challenges such as ammonia accumulation and earthworm population management persist. The study suggests that while flush toilets remain the most socially acceptable option, integrating vermicomposting into sanitation systems requires overcoming significant obstacles, including public health concerns and user acceptance. This research highlights the potential of vermicomposting to close the loop in human–nature interactions and promote sustainable waste management practices.

Contributions 3, 7, and 8 focus on public knowledge, attitudes, and practices (KAP) regarding sustainability in waste management. Contribution 3 examines public KAP regarding single-use plastic bags in the UAE, emphasizing the importance of understanding local behaviors in promoting sustainable practices. The study revealed that the UAE generally demonstrates a favorable attitude towards sustainability, with a positive correlation between increased knowledge and more sustainable practices. Individuals with higher environmental awareness also tend to engage in more sustainable behaviors. This research suggests that targeted educational interventions and policies, such as those focusing on recycling and reducing plastic bag use, could further enhance public engagement with environmental issues. This study is critical for informing effective policy interventions in plastic waste management.

Contribution 7 evaluates KAP regarding plastic pollution among Malaysians. The study found that overall public knowledge and practices were suboptimal, with younger individuals (18–30 years) demonstrating lower levels of awareness and action than older age groups. This study highlights the need for education and intervention strategies to promote better waste management practices. These interventions may include raising awareness of plastic pollution through formal education, increasing recycling facilities, and encouraging responsible consumer behaviors. These findings suggest that targeted age-specific strategies can effectively reduce plastic pollution in Malaysia.

Contribution 8 investigates KAP regarding waste segregation in the UAE. Their study found that while residents exhibit positive attitudes towards sustainability, waste segregation practices are still lacking, with education and gender showing significant correlations with better practices. This study recommends tailored educational campaigns that address specific sociodemographic factors to improve waste segregation behavior. This research contributes to the growing body of knowledge on how cultural, social, and academic factors influence sustainable waste management practices and suggests a path forward through improved public engagement and policy reforms.

With the increasing demand for indium in electronic devices, there is growing pressure to identify sustainable solutions for recycling this valuable material. Contribution 4 presents a patented technology (circular strategies for indium recovery from ground panels, SCRIPT) for recovering indium from end-of-life LCD panels, demonstrating a recovery efficiency of over 90%. This study focuses on optimizing this process at the bench scale and assessing its environmental and economic sustainability. The findings indicate that the process effectively recovers indium and converts the residual materials into concrete, providing a useful byproduct. This research demonstrates the potential for indium recycling to contribute to a circular economy, reduce mining dependence, and support the sustainability of high-tech industries. This study emphasizes the viability of this recycling technology,

particularly at high indium concentrations, and suggests that such methods can be scaled up for global applications.

The cement industry contributes significantly to global greenhouse gas emissions and has considerable potential for improvement through alternative resources and fuel use [14]. Contribution 9 examines the environmental impact of utilizing alternative resources and waste-based fuels in Korea's cement industry. The study reveals that co-processing with alternative fuels, such as waste-derived energy sources, can reduce emissions by approximately 106.9 kg of CO_2 per ton of cement. Additionally, utilizing alternative materials such as silica stone and limestone helps reduce the overall carbon footprint. This research demonstrates that the cement industry can significantly contribute to climate change mitigation by adopting more sustainable practices, thus offering both environmental and economic benefits such as cost savings and extended landfill lifespans.

Plastic pollution, particularly from polyethylene terephthalate (PET), is a pressing global issue [15]. Contribution 13 explores the challenges and opportunities in recycling PET waste, focusing on global efforts to reduce the environmental impacts of plastic pollution. This investigation examines initiatives such as extended producer responsibility (EPR) systems, plastic prohibitions, and deposit-return schemes to promote PET recycling. Researchers have highlighted India's efforts to implement recycling strategies and advocate for global collaboration among governments, industries, and consumers to increase recycling rates. This study emphasizes that effective PET management and recycling reduces plastic waste and generates economic opportunities through recycled products, thereby contributing to a more circular economy.

Contributions 1, 3, 4, 7, 8, 9, and 13 provide diverse insights into sustainable practices across various sectors, from waste management to resource recovery. Contributions 1 and 4 provide innovative solutions for resource recovery through composting and metal recycling, respectively, emphasizing the significance of circular economy principles in waste management. Contributions 3 and 7 elucidate the critical role of public awareness and education in promoting sustainable behaviors, particularly concerning plastic pollution. Contribution 8 elucidates the intricacies of waste sorting techniques, which are crucial for optimizing recycling mechanisms in metropolitan areas. Contribution 9 indicates the potential for industries such as cement to contribute substantially to emission reductions, while Contribution 13 focuses on the global importance of PET recycling in mitigating plastic waste. Collectively, these studies reinforce the necessity for integrated strategies that combine technological innovation, public engagement, and policy reforms to address the complex environmental challenges faced by contemporary society.

Sustainable agricultural practices require a comprehensive understanding of the complex interactions among energy, water, land, and waste. Contribution 12 presents a detailed analysis of these nexus elements in Cameroon, utilizing input–output modeling and location quotient (LQ) analysis for ten regions from 2009 to 2018. The findings indicate that water usage and waste production are the most significant components of the nexus, with water accounting for 67.88% of agricultural water withdrawal and waste, contributing to 97.81% of the total waste produced. This study identifies the central, littoral, and western regions as key areas for agricultural production and emphasizes the importance of considering regional variations when developing strategies for agricultural sustainability. This study provides valuable insights into how water, waste, and land management can contribute to more sustainable agricultural systems, suggesting that these elements should be integrated into national strategies for food security and sustainable resource utilization.

Nature-based solutions (NBSs) present a promising approach for addressing challenges within the Water–Ecosystem–Food (WEF) nexus, offering environmental, economic, and social benefits. Contribution 15 describes a comprehensive methodology developed

in the European Union-funded 'LEarning and action alliances for NexuS EnvironmentS (LENSES)' project to assess the implementation of NBSs in six pilot areas across five Mediterranean countries. The results demonstrate that NBSs contribute to improved water distribution, enhanced food security, and ecosystem preservation while supporting adaptation to climate change. This study emphasizes the significance of participatory approaches, engaging multiple stakeholders to gain insights into local challenges, and facilitating the operationalization of the WEF nexus. By identifying context-specific vulnerabilities and solutions, this study highlights the potential of NBSs to enhance the resilience and sustainability of agri-food systems in the Mediterranean region. This study provides a valuable framework for future policy development and NBS implementation in similar contexts.

Contributions 12 and 15 underscore the importance of a systems approach to sustainability, emphasizing the need to balance resource use across sectors and to adopt nature-based solutions to enhance environmental resilience. Both studies highlight the value of the local context in identifying effective solutions in terms of agricultural practices or environmental interventions and emphasize integrating these approaches into broader policy frameworks to ensure long-term sustainability and food security. These studies also demonstrate the growing recognition of the Water–Ecosystem–Food nexus as a critical area of focus, particularly in regions facing climate change and resource scarcity. Integrating technological innovation, nature-based solutions, and participatory policymaking is crucial to address the complex challenges of sustainability. Furthermore, the findings suggest that understanding local environmental dynamics and engaging stakeholders in decision-making processes can improve the effectiveness of interventions and foster more sustainable behaviors across different sectors.

It is imperative to develop and implement innovative solutions to address the challenges of air, water, food, and waste management. The intersection of technology, policy, and public awareness presents a unique opportunity to recover from a crisis and create a more sustainable and healthier world for future generations. It is no longer adequate to consider environmental sustainability a peripheral concern. Air, water, food, and waste management must be integrated into the fundamental structures of the economy, society, and governance systems. The urgency of these issues, the interconnectedness of these resources, and the need for global cooperation should be acknowledged. The imperative for innovation and action is immediate, as humankind's health, planet, and future depend on it.

While the diverse novel approaches introduced in this Special Issue demonstrate significant potential, their success is contingent on collaboration between governments, businesses, and communities. Policymakers should establish regulatory frameworks that provide incentives for sustainability and attract investments in green technologies. Implementing a wide-ranging public education initiative is crucial for fostering deeper comprehension among all members of society regarding sustainable practices and facilitating their active participation in environmental conservation efforts. Therefore, solutions cannot rely solely on innovation to ensure a sustainable future. This necessitates a paradigm shift in society's interactions with the planet. Cross-sectoral collaboration can ensure the development of sustainable ecosystems by incorporating innovative approaches, essential for sustenance and improved quality of life in the coming years.

The imperative to create a better world has transcended idealistic aspirations and rhetorical discourse, thus becoming an urgent necessity. By implementing innovative strategies for air purification, water management, food production, and waste processing, substantial advancements can be realized towards establishing a more sustainable and ecologically balanced environment that honors planetary and human welfare. It is crucial

to undertake resolute measures to safeguard the future in natural ecosystems that thrive harmoniously with human progress, ensuring a viable legacy for subsequent generations.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
COVID-19	COronaVIrus Disease of 2019
EPR	Extended Producer Responsibility
IoT	Internet of Things
KAP	Knowledge, Attitudes, and Practices
LD	Linear Dichroism
LENSES	LEarning and action alliances for NexuS EnvironmentS
MDPI	Multidisciplinary Digital Publishing Institute
NBS	Nature-Based Solution
PET	PolyEthylene Terephthalate
SCRIPT	Circular Strategies for Indium Recovery from Ground Panels
WEF	Water–Ecosystem–Food
WEFE	Water–Energy–Food–Ecosystem
WHO	World Health Organization

List of Contributions

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The Use of Some Species of Bacteria and Algae in the Bioremediation of Pollution Caused by Hydrocarbons and Some Heavy Metals in Al Asfar Lake Water

Fatimah Altammar [1,†], Nermin El Semary [1,2,*,†] and Munirah Aldayel [1]

[1] Biological Sciences Department, College of Science, King Faisal University, Al-Ahsa 31982, Saudi Arabia; 220000215@kfu.edu.sa (F.A.); maldayel@kfu.edu.sa (M.A.)
[2] Botany and Microbiology Department, Faculty of Science, Helwan University, Cairo 11795, Egypt
* Correspondence: nelsemary@kfu.edu.sa
† These authors contributed equally to the manuscript.

Abstract: Pollution is the biggest environmental and health threat in the world. Conventional treatments of polluted habitats require the removal of pollutants contaminating the environment, but removal methods are costly and involve high power consumption. This research aims to investigate the potential for bioremediation and proposes an alternative source for implementing it that is cheaper and more environmentally friendly. The phycobioremediation experiment used hydrocarbon- and heavy-metal-polluted water from Al Asfar Lake, AlAhsa, KSA. The isolation and characterization of the lake's predominant microalgae and associated bacteria were carried out. Monoalgal cultures of the dominant genera of algae were employed for the treatment of contaminated water and soil samples. The concentrations of the heavy metals and hydrocarbons in these samples were determined before and after the treatments by using atomic absorption spectroscopy (for heavy metals) and gas chromatography (for hydrocarbons). From the initial assessments, the levels of manganese, copper, and chromium were high, with chromium being the highest. Three microalgal isolates were identified: two coccoid, with one being blue-green and the other green, and one filamentous cyanobacterium. These species were the most efficient in removing heavy metals and dangerous hydrocarbons. Molecular characterization revealed *Chlorella* sp. and *Geitlarianema* sp. to be the most promising for bioremediation. The present work sheds light on the prospect of using algal and bacterial consortia for optimized, safe, and eco-friendly pollution amelioration.

Keywords: microalgae; bioremediation; bacteria; environmental cleanup; hydrocarbons; heavy metals; Al Asfar Lake

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1. Introduction

The greatest problem of the highest priority today is environmental pollution, which includes air, water, and soil pollution mainly caused by anthropogenic activities. Activities like burning fossil fuels and applying pesticides, insecticides, and herbicides has tremendously increased the levels of pollution worldwide [1]. For instance, the contamination of water reservoirs affects water quality and intoxicates aquatic species. Therefore, there is a dire need for the introduction of proper and sustainable pollution management techniques that will help in remediation [2,3]. In that regard, microbial bioremediation represents a promising eco-friendly solution for environmental pollution, especially when using bacteria and microalgae to restore a contaminated niche [4]. Using the microbial bioremediation approach is far more advantageous than traditional physico-chemical techniques. The latter are expensive and hazardous. Biological remediation, on the other hand, is relatively inexpensive and eco-friendly. However, the time taken to remediate sites contaminated with heavy metals depends on the ability of the specific organisms employed in the process and the factors limiting their growth and bioremediating activity.

Various bacteria, fungi, and plants have shown their potential to biologically decontaminate polluted land and water and have been extensively reviewed. Algae are recognized as the most effective biosorbents because of their special metabolites/storage products. Some of the experimentally proven algal biosorbents belong to *Spirogyra*, *Sargassum*, and *Lyngbea* [5,6]. On the other hand, some heavy metals are poisonous to microorganisms, which represents a major limitation of microbial remediation approaches [7]. This impediment, however, is outweighed by the fact that some microbial strains possess the ability to develop coping/resistance mechanisms like metal detoxification [8].

Apart from photosynthetic aquatic microorganisms such as microalgae (including blue-green algae or cyanobacteria), some associated heterotrophic bacteria can also contribute to the elimination of contaminants. These unique microorganisms possess unique metabolic, enzymatic, and cellular functions [1–4]. Microbial bioremediation based on algae and bacteria in particular is an attractive method for the restoration of polluted sites. Al Asfar Lake, Eastern Province, Kingdom of Saudi Arabia, is a site with huge development potential as a recreational lake, but eco-friendly efforts are needed to clean up the lake from wastes from agricultural drainage and industrial and domestic effluents in order to eliminate both organic and inorganic pollutants. Pollutants that are predominant in the lake are heavy metals and hydrocarbons. Manganese (Mn), copper (Cu), and chromium (Cr), in particular, are higher than their standard levels. Many researchers have discussed the risks of heavy metals and possible remediation options ([3,4,7,8] and references therein). Heavy metals are harmful to health, and repeated exposure can lead to neurological damage, respiratory disorders, and cancer. Among all the existing forms of chromium pollutants in the environment, Cr (VI), i.e., a hexavalent ion, is the most toxic form because of its strong oxidizing ability. However, the other form of chromium, Cr (III), i.e., a trivalent ion, is highly reactive to carboxyl and thiol groups and therefore disrupts the structure and function of various enzymes. Cr ionic complexes within the cells form electrostatic interactions with the phosphate groups in DNA molecules to negatively affect essential cellular processes such as transcription, translation, and replication. These ions are produced due to various industrial activities, such as oil well drilling, which is quite relevant to Eastern Province, KSA, where there are many oil drilling sites. Industries like paper manufactories, electroplating, and textiles all contribute to pollution.

Exposure to high contents of Cr may damage the size and diversity of the microbial population. The high toxicity and mutagenic nature of Cr have raised serious concerns for human health, which range from nasal irritation to cancer. The release of different forms of Cr due to the use of Cr-plated utensils induces disorders such as ulcers, dermatitis, bronchitis, hemorrhage, skin cancer, and DNA damage. Another heavy metal is copper, which is considered an essential trace element in minute concentrations. Therefore, it is crucial for various physiological activities but is largely toxic for various organisms in high concentrations. Increased accumulation of Cu in the environment has been observed over the past few decades. The high ductility and thermal conductivity of copper make it an ideal candidate for engines, and most of the agricultural practices require tractors and other mobile vehicles for agronomic practices. Human industrialization has also led to substantial increases in Cu levels in both the terrestrial and aquatic environments. Additionally, the use of fungicides and pesticides, which contain copper in addition to other salts, like Bordeaux mixture, continuously add Cu to the agricultural runoff.

Exposure to high levels of Cu is toxic to the human body, and such effects become pronounced with frequent exposure. The copper ions Cu(I) and Cu(II) catalyze the formation of reactive oxygen species (ROS) through the Haber–Weiss reactions, culminating in the formation of free radicals that can injure all forms of biomolecules. However, their buildup to even tolerable levels causes severe irritation and corrosion on the mucous membranes of many organs. This can lead to angiogenesis, infection, and inflammatory responses, which, in the context of the CNS, can lead to irritation and, thus, depression. Fatally high concentrations of copper also lead to the formation of necrotic zones in the liver and kidneys.

With regard to hydrocarbons, petroleum, and polyaromatic hydrocarbons (PAHs), in particular, those present in wastewater are lethal to all forms of life in water bodies, interfere with the whole ecosystem, and should be eliminated [9]. Organic pollution sources include oil extraction and movement and the incomplete combustion of petroleum products. Among all the pollutants, oil is the most significant contributor of organic pollution for both types of settings: terrestrial and water. By the same measure, deforestation and the burning of trees also cause the release of hydrocarbons into the air and erase the natural carbon dioxide sink. The increase in the level of organic pollution from domestic, industrial, agricultural, and commercial discharge is a major concern according to the environmentalists.

Therefore, attempts must be made to isolate and characterize microbial strains from polluted ecosystems. Such microbes will most probably be adapted and resistant to the environment in question due to their origin from contaminated sites. The present study focuses on trying to pinpoint some of the most abundant microbial strains that make up algal–bacterial consortia in Al Asfar Lake. It also looks at the current status of heavy-metal contamination of lake water and the bio-remediation potential of microbial consortia. Also, this research focuses on the detection of hydrocarbons and the possibility of their biodegradation. The main purpose is to offer a cost-effective, eco-friendly biological solution to the pollution of the lake, which in turn contributes to both environmental restoration and sustainability.

2. Methodology

2.1. Collection of Algal Samples

Water samples containing algae were collected from Asfar Lake, Al-Hassa, Kingdom of Saudi Arabia, in December 2022.

2.2. Isolation, Purification, and Identification of Algal Samples

Algal biomass was extracted from the water samples by using centrifugation at 3000 rpm; the supernatant was discarded, whereas the biomass pellet was spread on BG-11 medium (Table 1) solidified by agar for isolation and purification. Pure monoalgal cultures were established by repeated streaking on agar plates. The initial identification of cultures was performed by using light microscopy according to Raklami [10].

Table 1. BG-11 medium composition.

Component	**Stock Solution ($g \cdot L^{-1}$ dH_2O)**	**Quantity Used/L**
Fe citrate solution	–	1 mL
Citric acid	6	1 mL
Ferric ammonium citrate	6	1 mL
$NaNO_3$	–	1.5 g
$K_2HPO_4 \cdot 3H_3O$	40	1 mL
$MgSO_4 \cdot 7H_2O$	75	1 mL
$CaCl_2 \cdot 2H_2O$	36	1 mL
Na_2CO_3	20	1 mL
$Na_2EDTA \cdot H_2O$	1.0	1 mL
Trace metal solution	–	1 mL
Trace element solution composition		
Component	Stock Solution ($g \cdot L^{-1}$ dH_2O)	Quantity Used/L
H_3BO_3	–	2.860 g
$MnCl_2 \cdot 4H_2O$	–	1.810 g
$ZnSO_4 \cdot 7H_2O$	–	0.22 g
$CuSO_4 \cdot 5H_2O$	79.0	1 mL
$Na_2MoO_4 \cdot 2H_2O$	–	0.391 g
$Co(NO_3)_2 \cdot 6H_2O$	49.4	1 mL

2.3. Morphological Examination and Establishment of Monocultures

Through the use of light microscopy, it was revealed that the water samples were predominantly full of three algal species. Those isolates were isolated and labelled C1, C2, and F; two of them were unicellular coccoids; one was a cyanobacterium and one a green alga. The cyanobacterium was an unbranched non-heterocystous filamentous strain.

2.4. Isolation and Purification of Bacterial Strains

The heterotrophic bacteria associated with the algal isolates from Al Asfar Lake were isolated by using nutrient agar. Pure strains were grown from the colonies by isolating them on solid medium and keeping them in a refrigerator to run the experiments later.

2.5. Detection of Heavy Metals by Chemical Analysis of Samples

The water samples of Al Asfar Lake were analyzed chemically by using ICP-OES and PerkinElmer Titan MPS for the presence of heavy metals, which included Li, Co, Ni, Zn, Cd, As, and Pb. The ICP-OES (Inductively Coupled Plasma Optical Emission Spectroscopy) system and PerkinElmer Titan MPS equipment are both made by PerkinElmer, USA.

2.6. Chemical Element Analysis after Incubation with Algal Consortium

A unified amount of algal biomass of each species, determined gravimetrically, was added to the filtered lake water samples and incubated for 2 weeks. The elemental composition of water before and after incubation with algae was determined by using the ICP-OES (Inductively Coupled Plasma Optical Emission Spectroscopy) system.

2.7. Molecular Identification

Microalgae that showed the highest bio-remediating activity were identified by using a polyphasic approach which combines the morphological characters with molecular characterization and phylogenetic inference of the isolates. The molecular method included PCR using universal algal primers [11], with the template being genomic DNA that was previously extracted by using method in [12]. Those primers targeted part of the 23S rDNA gene within the cyanobacterial genome. This was followed by phylogenetic analysis and tree reconstruction to reveal their evolutionary background.

2.8. Polyaromatic Hydrocarbon Analysis

The water samples were tested for the presence of polyaromatic hydrocarbons, and the samples of water were incubated with the algal biomass for a month [13].

3. Results

3.1. Microscopic Examination of Predominant Microbial Consortium Members

The experimental findings of this study identify three microalgal strains and their heterotrophic bacteria from Al Asfar Lake. The five microalgal strains comprised two unicellular coccoid forms: a blue-green alga (cyanobacterium) and a green alga; a third was a filamentous non-heterocystous cyanobacterium. The filamentous strain, which had an unbranched thin trichome with rounded ends, did display motility though gliding. These strains were identified as C1 (the first coccoid unicellular type), C2 (the second coccoid unicellular type), and F1 (the filamentous lytic type) and proved to be cultivable on liquid BG-11 medium.

Apart from microalgae, four heterotrophic bacterial strains affiliated to the algal cultures were also identified and given codes A1, A2, B, and C1. After Gram staining, bacterial strains A1, A2 and C1 were found to be Gram-negative, and strain B was found to be Gram-positive. Incubation with spore stain agents showed that all the bacterial isolates were vegetative cells, but none of the cells had endospores. Therefore, these results enrich the information and knowledge concerning the microbial consortia connected with algae in aquatic ecosystems. Table 2 lists some of the morphological characteristics of bacteria in the microbial consortium.

Table 2. Colony characteristics of bacteria associated with algal strains in microbial consortium.

Bacterial Pathogen Strain (Code)	Colony Color	Size of Colony (Diameter)	Shape	Texture	Elevation
A1	Orange	2 mL	Round	Shiny, smooth	Flat
A2	Yellowish	1 mL	Round	Shiny, smooth	Flat
B	Light, orange	2 mL	Round	Shiny, smooth	Flat
C1	White	2.5 mL	Round	Shiny, smooth	Flat
C2	White	1.5 mL	Round	Shiny, smooth	Flat

3.2. Bioremediation of Water Samples from Al Asfar Lake

The chemical analyses of water from Al Asfar Lake without algal treatment by using ICP showed the presence of some heavy metals above standard levels, namely, Mn, Cu, and Cr. The latter was present in much higher concentration than the standard level. Table 3 shows the original concentrations of elements in lake water, and Table 4 shows the element concentration after incubation with algal samples at two different culture volumes for each algal strain. It was notable that water samples were already green in color, indicating the profuse growth of algae. A unified filtered volume of each water sample of Al Asfar Lake was incubated with two volumes (10 and 15 mL) of a one-month-old algal culture from each isolate type corresponding to 0.1 and 0.15 gm fresh weight of algal biomass. The treated water samples were incubated for a month and reanalyzed for their element contents (Table 5). A control sample that was not treated with algal cultures was also analyzed. The addition of the three algae caused a noticeable decrease in the metal concentration but with differential impacts (Table 6). The most bio-remediating algal samples were the green coccoid alga and the filamentous cyanobacterium. They caused the almost complete removal of metals that were previously present above standard concentrations.

Table 3. Analysis of chemical element in water from Al Asfar Lake by using ICP.

Chemical Element	Concentration Average	Concentration RSD	Concentration SD
Mn	1.678	35.1%	0.6 ppm
Co	0.994	0.5%	0.0 ppm
Cu	0.769	92.7%	0.7 ppm
Zn	1.059	0.3%	0.0 ppm
Cd	1.037	0.3%	0.0 ppm
Pb	1.060	1.2%	0.0 ppm
As	0.753	0.6%	0.0 ppm
Fe	0.887	0.2%	0.0 ppm
Ni	1.032	0.3%	0.0 ppm
Cr	0.588	259.5%	1.5 ppm
B	1.0090	0.3%	0.0 ppm

Table 4. Bioremediation of metals in water samples from Al Asfar Lake metals based on algal treatment. C1 denotes the coccoid cyanobacterium; C2 denotes the coccoid green alga; F3 denotes the filamentous non-heterocystous cyanobacterium. For each algal isolate, different volumes of cultures were used in the bioremediation experiment. Values reported here are the average concentrations detected. The value 0.00 ppm indicates that the element concentration is below the detection limit of the device. Every element has its own detection limit below which it cannot be detected by the device.

Sample	(C1) 10 mL Culture	(C1) 15 mL Culture	(C2) 10 mL Culture	(C2) 15 mL Culture	(F) 10 mL Culture	(F) 15 mL Culture
Mn	0.511 ppm	0.220 ppm	0.126 ppm	0.081 ppm	0.362 ppm	−0.668 ppm
Co	0.004 ppm	0.002 ppm	0.002 ppm	0.001 ppm	0.002 ppm	0.003 ppm
Cu	0.105 ppm	−0.068 ppm	0.282 ppm	−0.096 ppm	0.149 ppm	0391 ppm
Zn	0.029 ppm	0.000 ppm	0.030 ppm	0.036 ppm	0.082 ppm	0.100 ppm

Table 4. *Cont.*

Sample	(C1) 10 mL Culture	(C1) 15 mL Culture	(C2) 10 mL Culture	(C2) 15 mL Culture	(F) 10 mL Culture	(F) 15 mL Culture
Cd	0.002 ppm	0.017 ppm	0.000 ppm	0.000 ppm	0.000 ppm	0.000 ppm
Pb	0.018 ppm	0.008 ppm	0.019 ppm	0.020 ppm	0.027 ppm	0.018 ppm
As	0.011 ppm	0.008 ppm	0.006 ppm	0.008 ppm	0.007 ppm	0.005 ppm
Fe	0.060 ppm	0.053 ppm	0.058 ppm	0.062 ppm	0.027 ppm	0.037 ppm
Ni	0.004 ppm	0.0 03 ppm	0.002 ppm	0.004 ppm	0.003 ppm	0.001 ppm
Cr	−0.103 ppm	−1.116 ppm	−1.642 ppm-	0.172 ppm	−0.400 ppm	−2.307 ppm
B	1.427 ppm	1.544 ppm	1.426 ppm	1.676 ppm	1.737 ppm	1.419 ppm

Table 5. Hydrocarbon composition of water sample from Al Asfar Lake (control).

Compound Name	%	Retention Time (Rt), min
Phenol, 2,4-bis(1,1-dimethylethyl)	0.94	7.597
Cycloheptasiloxane, tetradecamethyl	3.62	7.801
Cyclooctasiloxane, hexadecamethyl	7.69	9.2
Cyclononasiloxane, octadecamethyl	8.15	10.365
Cyclodecasiloxane, eicosamethyl	7.38	11.423
Cyclooctasiloxane, hexadecamethyl	8.7	12.635
Cyclononasiloxane, octadecamethyl	11.72	13.723
Tetracosamethyl-cyclododecasiloxane	13.56	14.759
Tetracosamethyl-cyclododecasiloxane	17.48	16.067
Tetracosamethyl-cyclododecasiloxane	20.76	17.836

Table 6. Hydrocarbon composition of water sample treated with *Chlorella* sp.

Compound Name	%	Retention Time (Rt), min
Phenol, 2,6-bis(1,1-dimethylethyl)	1.42	7.593
7-(1,5-Dimethylhexyl)-10,13-dimethyl2,3,4,7,8,9,10,11,12,13,14,15,16,17-tetradecahydro-1H-cyclopenta[a]phenanthren3-ol	72.14	14.341
Cholest-5-ene, 3.beta.-chloro	26.44	14.711

The monoalgal cultures are not axenic, and they are associated with heterotrophic bacteria. The removal of metals with the algal–bacterial consortium was the best with bioremediating strains C2 and F.

Briefly, in the case of lake water samples before algal bioremediation, manganese, copper, and chromium (Cr) were all higher than standard values (Table 5). Following algal treatments, all these elements were almost completely removed, especially when applying a higher volume of algal cultures (Table 4). The most efficient algal strains in bioremediation were the filamentous cyanobacterium and the green algal strain.

3.3. Characterization of Taxonomic Identity of Most Efficient Bio-Remediating Algal Strains Using Molecular Analysis and Phylogenetic Inference

According to the molecular characterization, the most bio-remediating algae was found to be a non-heterocystous filamentous blue-green alga (cyanobacterium) and a coccoid green alga. The taxonomic identity of the isolates was also established by molecular techniques and phylogenetic trees. The BLAST search returned 99%. The sequence was highly related to *Chlorella* sp.

It is also necessary to mention that BLAST determines the pairwise homologous alignments of a subject range with a particular sequence and an aligned sequence from the database, while the search in multiple sequences is beyond its capabilities. Rather, implicit homology is built by how the database sequences match up with the query. The case with sequences that only partially match is solved in BLAST by the inclusion of only the sequence with the highest score in the phylogenetic tree (Figure 1).

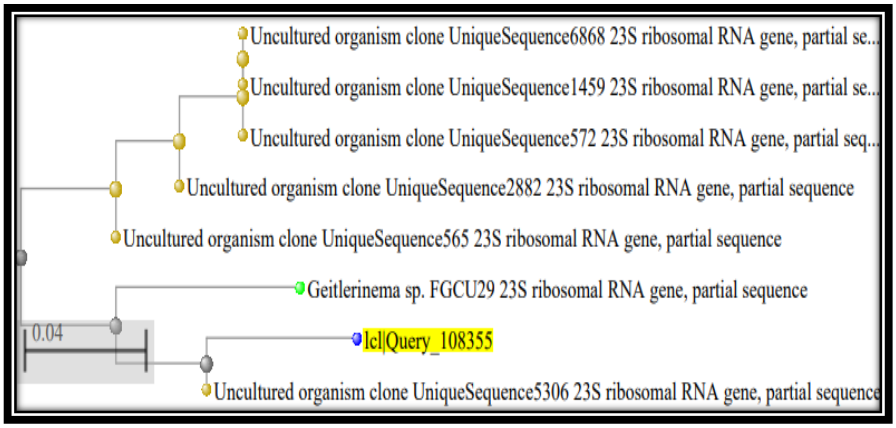


Figure 1. The Neighbor-Joining Phylogenetic tree of unicellular microalgae *Geitlerinema* sp. The green circle represents the closest match, whereas the yellow circles represent much further matches. The sequence in yellow is the sequence obtained for one of the bioremediating algal strains.

The BLAST search matched *Geitlerinema* sp. with 82.91% similarity. BLAST computes pairwise alignment between a query and database sequences but does not perform multiple alignments. An implicit alignment is constructed based on database sequence alignment to the query [14]. In cases where sequences barely overlap, only the higher-scoring sequence is included in the tree (Figure 1).

The BLAST search matched *Chlorella* sp. with 99.40% similarity. BLAST computes pairwise alignment between a query and database sequences but does not perform multiple alignments. An implicit alignment is constructed based on database sequence alignment to the query [6]. In cases where sequences barely overlap, only the higher-scoring sequence is included in the tree (Figure 2).

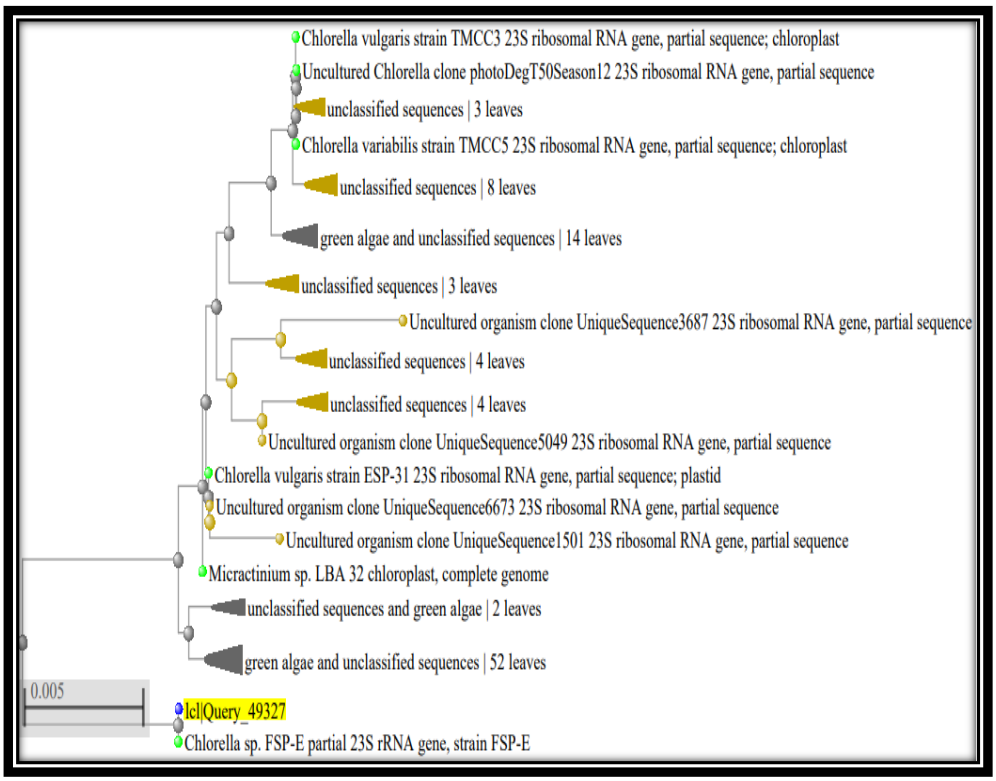


Figure 2. The Neighbor-Joining Phylogenetic tree of unicellular microalgae *Chlorella* sp. The green circle represents the closest match, whereas the yellow circles represent much further matches. The sequence in yellow is the sequence obtained for one of the bioremediating algal strains.

3.4. Polyaromatic Hydrocarbon Analysis

The hydrocarbons found in the water of Al Asfar Lake are listed in Table 7. The following chemicals were detected in the case of the control (Table 5) but were not present in the case of the sample treated with *Chlorella* sp. (Table 6), indicating its bioremediating activity that resulted in the removal of Cycloheptasiloxane, tetradecamethyl; Cyclooctasiloxane, hexadecamethyl; Cyclononasiloxane, octadecamethyl; Cyclodecasiloxane eicosamethyl; Cyclooctasiloxane, hexadecamethyl; Cyclononasiloxane, octadecamethyl; Tetracosamethyl-cyclododecasiloxane; Tetracosamethyl-cyclododecasiloxane; and Tetracosamethyl-cyclododecasiloxa

Table 7. Hydrocarbon composition of water sample treated with filamentous *Geitlernema* sp.

Compound Name	%	Retention Time (Rt), min
Phenol, 2,4-bis(1,1-dimethylethyl)	10.44	7.595
Cyclooctasiloxane, hexadecamethyl	5.11	9.197
Cyclononasiloxane, octadecamethyl	7.4	10.362
Cyclodecasiloxane, eicosamethyl	6.49	11.421
Cyclooctasiloxane, hexadecamethyl-	8.26	12.633
Tetracosamethyl-cyclododecasiloxane	11.44	13.721
Tetracosamethyl-cyclododecasiloxane	13.89	14.755
Tetracosamethyl-cyclododecasiloxane	17.53	16.064
Tetracosamethyl-cyclododecasiloxane	19.44	17.833

On the contrary, the sample treated with the filamentous cyanobacterium (*Geitlernema* sp.) showed the presence of most of those polyaromatic hydrocarbons that were detected in the control, showing its very limited bioremediating ability (Table 7), which only resulted in the removal of Cycloheptasiloxane, tetradecamethyl.

4. Discussion

The study investigates the effects of algal treatment on reducing and bioremediating heavy metals in water samples from Al Asfar Lake. The control sample showed higher than normal concentrations of manganese, copper, and cadmium. Through algal treatment, the levels of all those metals dropped, indicating the complete or near complete removal of those metals. The results suggest that algal treatment effectively removed those elements from the water samples. Indeed, ref. [5] reported that phycobioremediation using *Chlorella* sp. for cleaning up contaminated water reservoir was feasible, efficient, and eco-friendly.

The study shows that algae have strong bioremediation capacity for some heavy metals present in the water samples from Al Asfar Lake, particularly the non-heterocystous filamentous blue-green alga (cyanobacteria) and the green alga. These algae show promise for cleaning up the environment by drastically lowering the concentrations of heavy metals like Mn, Cu, and Cr. The use of indigenous microorganisms, including green microalgae, to eliminate toxic levels of Cr pollutants has gained particular attention during recent decades [6]. The use of biological techniques produces little to zero secondary waste during bioremediation operations [6]. Moreover, the employment of both Gram-positive and Gram-negative bacteria is known to decontaminate the chrome-polluted environment in the vicinity of tanneries and electroplating industries [6]. Singh et al. (2013) [15] have demonstrated the excellent potential of *Bacillus cereus* to remove 72% of Cr (VI) at a concentration of 1000 μg/mL chromate. Interestingly, these bacteria were able to maintain their Cr removal potential in a broad range of temperature and pH [15]. On the other hand, the bioremediation of copper is possible by utilizing certain Cu-tolerant microorganisms [16]. Some specific bacteria and microalgae reduce Cu levels by immobilizing the ions through various bioremediation strategies, such as bioleaching to remove ex situ solids which contain Cu and bioaugmentation to increase the rates of in situ Cu removal [16].

Several bioremediating mechanisms are used by microalgae and cyanobacteria to clean up heavy-metal pollution. These include both extra- and intracellular strategies, such as adsorption, the binding of metal ions to chemicals on the outer surface, and/or-the intake

of metal ions within their microbial cells, followed by internal detoxification; these cellular strategies limit the toxic effects of heavy metals. These mechanisms are summarized in [17] (and references within).

To remove heavy metals extracellularly, the composition of the cell wall and the presence of extracellular polymeric substances play crucial roles [17,18]. The large biomolecules in the cell wall, such as carbohydrates, lipids, and proteins, perform multiple functions, including giving an overall negative charge to the cell wall because of functional groups such as amino, carboxyl, phosphate, and phenol groups. [17]. The attachment of heavy-metal cations thus occurs on the cell surface and is not dependent on cellular metabolism [17]. However, the removal strategy largely varies with the genus and species of algae utilized [17]. In some algae, essential ions such as calcium, potassium, and magnesium bind to the cell surface but are reversibly substituted in the presence of excessive contents of heavy metals by a process known as 'ion exchange' [17]. The intracellular accumulation of heavy metals, however, depends on cellular metabolism [17]. The transport of heavy metals ions is largely dependent on active and/or passive transport pathways [17]. The intracellular uptake strategy, on the other hand, involves the active transport of heavy metals via negatively charged groups of biopolymers on the cell surface. The hydrophilic nature of heavy metals allows for their transport across the cell membrane with the help of specific intrinsic proteins known as metal transporters. Afterwards, the detoxification of heavy metals occurs via various pathways, including the production of metal binding proteins such as phytochelatin to chelate heavy metals, the interaction of heavy metals with thioneins for the formation of metallothioneins, the formation of complex interactions between heavy metals and poly-phosphate complexes, the sequestration of heavy-metals ions into vacuoles to reduce toxic effects, and increased activity of metal efflux systems to expel metal ions in case of extremely dangerous heavy-metal levels [17,18]. The intracellular detoxification and compartmentalization of heavy-metal ions is followed by the transformation of heavy-metal ions from the most toxic state to a relatively less toxic state, which may be performed by enzymes or a biochemically mediated mechanism. For example, the reduction of hexavalent chromium to a trivalent oxidation state makes chromium comparably less toxic and stable [17,18].

Furthermore, the study highlights the activity of algae in the removal/breakdown of polycyclic aromatic hydrocarbons, or PAHs, underscoring their significance in bioremediation initiatives.

Polycyclic aromatic hydrocarbons (PAHs) are the largest group of hydrocarbons with two or more fused benzene or pentacyclic rings [19]. These hydrocarbons are naturally present in coal, crude oil, and gasoline [19]. Coal-tar pitch, creosote, and asphalt produced from fossil fuels are also rich in PAHs [20]. Natural production of PAHs also occurs during forest fires and volcano eruptions. Relatively less soluble in water, PAHs are highly soluble in lipids [20]. A fraction of PAHs may decompose under ultraviolet light [21]. Some microorganisms are also capable of degrading aromatic hydrocarbons [21].

PAHs have attracted serious attention in recent years because of their detrimental effects on human health [20]. In fact, eight PAHs are typically regarded as possible carcinogens (Car-PAHs) [20]. These include chrysene, dibenzo(a,h)anthracene, benzo-anthracene, benzo-fluoranthene, indeno(1,2,3-cd)pyrene, benzo(k)fluoranthene, benzo(a)pyrene (B(a)P), and benzo(g,h,i)perylene [20]. Even PAHs which are not carcinogenic may still behave as synergists [20]. The increased production of PAHs is due to their ever-spreading use in research, medicines, dyes, plastics, and pesticides [19]. Indeed, our findings indicate their presence in large quantities in Al Asfar Lake water, and only *Chlorella* sp. was able to remove/breakdown these harmful chemicals.

The results suggest that algae, and more specifically *Chlorella* sp. and a non-heterocystous filamentous blue-green alga (*Geitlerinema* sp.), have great potential for the bioremediation of water samples from heavy metals, but *Chlorella* sp. alone has great potential for hydrocarbon bioremediation.

With regard to hydrocarbon pollution, some hydrocarbon compounds are reported to be pollutants, such as T*etracosamethylcyclododecasiloxane*, which is a pollutant present in the process of textile enhancements and pretreatments with ozone (https://www.chemicalbook.com/ChemicalProductProperty_EN_CB61436019.htm, accessed on 25 June 2024).

In addition, another chemical detected in the analysis was Octamethylcyclononasiloxane, which is used as an antimicrobial agent (https://amp.chemicalbook.com/ChemicalProductProperty_EN_CB41410749.htm, accessed on 25 June 2024). Compounds like Cyclononasiloxane are reported to result from some plant extracts and are also found in agricultural waste [22]. PAHs may be adsorbed by several particles [19]. These particle-bound PAHs are believed to be significantly hazardous substances to the well-being of humans, as they can enter in their bodies through breathing [19]. The commercial production of naphthalene—a PAH with the lowest boiling point and the highest volatility—to make mothballs and other chemicals has certainly escalated its contribution to organic pollution [20]. Although naphthalene occurs mostly in the vapor phase and its deposition on different surfaces is small if compared with other PAHs, the use of camphor balls (made with naphthalene) in the wardrobe has increased its levels in domestic environments [20]. Thus, the carcinogenic or mutagenic effects caused by increasing quantities of PAHs are a serious concern for human health [20]. Tetracosamethyl-cyclododecasiloxane was the most prevalent PAH (20.76%) among the control samples, which showed a range of PAHs. A distinct PAH composition, dominated by a molecule present in 72.14% of the sample, was detected in sample C2. Sample F3 likewise revealed a mixture of PAHs, with Tetracosamethyl-cyclododecasiloxane (19.44%) being the most common component. Hydrocarbon processing industries release a broad range of organic pollutants, including isoalkanes and aromatic hydrocarbons [23].

Overall, this research reports the significant ecological role of algal consortia in bioremediating freshwater environments [14]. Accordingly, this could prospectively be used to better deal with the conservation and management of similarly polluted aquatic habitats.

5. Conclusions

This research addressed the growing environmental concerns regarding the pollution of Al Asfar Lake and provided an eco-friendly solution through the use of algae as bioremediators. Algae have the ecological merits of being photosynthetic, mitigators of global warming, and removers of several heavy metals and hydrocarbons. Through their use, the ecological balance of the lake would be restored, and via their renewable growth, they would significantly contribute to the long-term sustainability of this vital water resource. The success of this study could pave the way for scalable, low-cost environmental restoration initiatives in similar ecosystems.

Author Contributions: F.A. was responsible for formal analysis, visualization, investigation, and co-writing the manuscript. N.E.S. was responsible for conceptualization, methodology, investigation; data analysis; visualization; project management and rewriting the manuscript. M.A. was responsible for methodology, investigation, visualization and funding. All authors have read and agreed to the published version of the manuscript.

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Perceived and Physical Quality of Drinking Water in Pavlodar and Akmola Rural Regions of Kazakhstan

Raikhan Beisenova [1,2,3,*], Kamshat Tussupova [4], Rumiya Tazitdinova [1], Symbat Tulegenova [5], Zhanar Rakhymzhan [1], Ainur Orkeyeva [1], Yerkenaz Alkhanova [1], Anar Myrzagaliyeva [6], Askar Nugmanov [1] and Aktoty Zhupysheva [7]

1 Environmental Management and Engineering Department, Faculty of Natural Sciences, L.N. Gumilyov Eurasian National University, Astana 010001, Kazakhstan; irm85@mail.ru (R.T.); r.zhanar@mail.ru (Z.R.); orkeevaa@mail.ru (A.O.); erkenaz_94-11@mail.ru (Y.A.); askar.nugmanov03@gmail.com (A.N.)
2 Landscape Ecology and Ecosystem Science Laboratory, Department of Geography, Michigan State University, East Lansing, MI 48824, USA
3 High School of Ecology, Yugra State University, Khanty Mansysk 628000, Russia
4 Department of Ecology, Kh. Dosmukhamedov Atyrau University, Atyrau 060011, Kazakhstan; kamshat.tussupova@gmail.com
5 Department of Botany, E.A. Buketov Karaganda University, Karaganda 100027, Kazakhstan; symbat.udeshova@mail.ru
6 Department Biology, Astana International University, Astana 010017, Kazakhstan; an.myrzagaliyeva@gmail.com
7 State Audit Department, L.N. Gumilyov Eurasian National University, Astana 010008, Kazakhstan; aktoty_nur@mail.ru
* Correspondence: raihan_b_r@mail.ru; Tel.: +7-7014334660

Abstract: Water quality in rural areas of developing countries is a notable problem. In this article, drinking water quality from eleven villages in the Pavlodar and the Akmola region of Kazakhstan was analyzed. Questionnaires of village respondents and chemical components of drinking water were analyzed to identify the quality of drinking water. In each of the villages, the chemical content varied depending on the source of drinking water. In the rural Pavlodar region, we observed that some cations and anions exceed the MPC. Respondents' perceptions of water quality are associated with water sources and physical components. For example, respondents' satisfaction by inside tap of central water systems' water was high, the answers of those whose water source was private wells showed more mixed satisfaction levels. The drinking water physical quality indicators are closely related to water mineralization and general hardness. The total microbial count of drinking water has a significant relationship with respondents' complaints about unpleasant taste, odor, and salinity. The relationship between perceived and physical water quality is a critical aspect of water resource management. By bridging the gap between scientific assessments and public perceptions, we can enhance public health, build trust in water management systems, and promote sustainability of water use.

Keywords: chemicals; quality; rural; source; drinking water; manganese; cations; anions; perseverance

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1. Introduction

Access to clean drinking water and adequate sanitation facilities are fundamental human rights, essential for maintaining public health. However, rural areas often face significant challenges in ensuring these necessities due to infrastructural, economic, and environmental constraints [1]. In regions like Pavlodar and Akmola in Kazakhstan, these challenges are particularly pronounced, affecting the quality of life and health outcomes of the residents. Sanitation infrastructure in rural areas is typically underdeveloped compared to urban centers. Studies have shown that inadequate sanitation can lead to significant public health issues, including the spread of waterborne diseases and environmental

contamination [2]. In rural Kazakhstan, many households still rely on outdoor toilets and basic sanitation facilities, which are often insufficiently managed and maintained [3].

In addition to sanitation challenges, water quality in rural areas is often compromised by both natural and anthropogenic factors. Groundwater, a primary source of drinking water in many rural regions, is susceptible to contamination from agricultural runoff, industrial pollutants, and inadequate waste disposal practices [4]. The presence of contaminants such as nitrates, heavy metals, and microbial pathogens in drinking water poses significant health risks. Previous research has highlighted the critical need for improved water quality monitoring and sanitation management in rural areas to mitigate these risks [5]. Effective interventions require a comprehensive understanding of the local context, including the types and conditions of sanitation facilities, the quality of drinking water sources, and the perceptions and practices of the local population regarding water and sanitation. Industrial and economic development in some developing countries has increased its impact on human health, agricultural activities, and ecosystems due to rising air and water pollution [6]. Moreover, rural areas in many countries continue to face serious problems caused by bacterial contamination of drinking water, perpetuating waterborne disease transmission, and highlighting the fecal–oral route as a common mode of transmission.

In Kazakhstan, as in other developing countries, issues are associated with ensuring equal access to drinking water and sanitation facilities in rural areas. State programs like "Ak Bulak" and "Nurly Zher" in Kazakhstan have been implemented to address these critical issues; however, their effectiveness is uncertain. Reliance on surface water and groundwater as primary drinking water sources, along with alternative collection methods like capturing precipitation, means there is a diversity of water sources of varying initial quality in rural Kazakhstan, often necessitating extensive treatment, especially of surface waters due to their generally poor condition. Works by foreign scientists have also highlighted water pollution in rural areas; for example, Organic amine pesticides (OAPs) are widely used in modern agriculture, and these compounds can contaminate drinking water sources in various ways. In the study Yang et al., samples of tap water (TW) and bottled water (BW) were collected from eight cities in the Yangtze River Delta urban agglomeration in China, and their total amine pesticide (TAP) levels were analyzed and showed that the total TAP concentration ($\sum$TAP) in TW (mean 11.06 ± 4.99 ng/L) was 29.4% higher than in BW (mean 8.55 ± 3.98 ng/L), and fewer species were detected OAP in BW. Moreover, long-term use of TW in some regions was associated with carcinogenic risk even in the acceptable range of TAPs, especially in men, with molinate being the major contributor (61.3%) to TAP exposure. Further analysis showed that the occurrence and health risks of OAPs in drinking water are mainly influenced by the quality of water sources and the technologies used at drinking water treatment plants (DWTPs) [7]. Sources of pollution are varied: industrial and household waste, agricultural runoff, as well as seepage from polluted surface reservoirs, oil wells, and water intakes [8].

Despite being of better quality compared to surface water, groundwater is not immune to contamination risks from various sources such as agricultural runoff and the improper disposal of liquid wastes, including industrial waste and leachates from municipal solid waste landfills. This highlights not only the complexities surrounding water source management but also the critical need for comprehensive water treatment solutions to ensure safety and potability [9]. This underscores the urgent need for comprehensive strategies to mitigate pollution, protect water resources, and ensure sustainable water management practices in Kazakhstan [10]. Rural areas face pressing environmental and public health challenges, particularly related to inadequate waste management and sanitation infrastructure. The lack of established public services in most populated areas and the loss of private sector waste collection services in rural areas of Kazakhstan have made significant contribution to environmental degradation. The situation is aggravated by the appearance of spontaneous dumps of household and industrial waste, as well as livestock farms near water bodies. This practice not only pollutes the environment but also poses a significant risk to water quality and public health [11]. Insufficient attention to wastewater disposal and quality

wastewater treatment in rural areas of Kazakhstan is explained by the relatively high costs of constructing rural sewerage systems and treatment facilities [12]. This financial barrier hinders the development of basic infrastructure, thereby jeopardizing water quality and the overall well-being of these rural communities.

Misalignment between perceived and actual water quality can lead to health risks. For example, if water appears clean but contains harmful microorganisms, it poses a threat to human health. Conversely, water that is safe but perceived to be of poor quality may lead people to use alternative, possibly unsafe sources. Public trust in water management authorities depends on the ability of such authorities to maintain high physical water quality and address public concerns effectively. Transparency in reporting water quality and addressing public concerns can enhance trust. Misperceptions about water quality can influence public support for environmental initiatives and policies. Accurate perceptions help foster responsible water use and conservation practices. Perceived poor water quality can impact tourism, property values, and economic activities in regions dependent on water resources. Ensuring high water quality and addressing perceptions can promote economic stability and community well-being. Moving forward, a balanced approach that integrates technical expertise with community engagement and education is essential for ensuring the long-term quality and availability of water.

Social science research typically uses the analysis of survey data, while research on chemical or biological monitoring of drinking water and surface waters uses the analysis of empirical or field data. This paper synthesizes a comprehensive method to show the relationship between the perceived quality and the basic chemical composition of drinking water from different sources.

The main research question is as follows: How does the water source type influence the quality of drinking water in rural areas and how does population perceive the water quality? The hypothesis is that the perceived water quality of residents is related to the physical quality of drinking water in rural areas depending on the sources of drinking water. By analyzing both the physical infrastructure and the residents' experiences and perceptions, we seek to identify key areas for intervention and improvement. The findings contribute to the development of targeted strategies to enhance water and sanitation services in these regions, ultimately improving public health outcomes and quality of life. The purpose of this study is to assess the quality of drinking water in rural areas of the Pavlodar and Akmola regions, considering different types of water supply systems. This water quality study is especially relevant given the diversity of water supply sources in the study areas.

2. Materials and Methods

2.1. Research Area

This study focuses on assessing the quality of drinking water within rural settlements of the Pavlodar and Akmola regions in Kazakhstan, which had substantial populations of 220,722 and 342,264 individuals in 2024, respectively [13]. Geographically, the Pavlodar region is situated in the northeast and the Akmola region is in the north of the Republic of Kazakhstan. The Pavlodar region's administrative structure comprises ten districts and multiple cities, settlements, rural districts, and villages, underscoring its significant spatial expanse and demographic diversity (Figure 1). The rural villages targeted in this study—Naberezhnoye, Chernoyarka, Gosplemstantsiya, Birlik, Efremovka, Zhertumsyk, Koryakovka, Shakat, Shoptykol, and Zhanatan in the Pavlodar region—represent a cross-section of the region's rural demographic, each with unique challenges and contexts in terms of water access and quality. Village Birsuat is in the Akmola region (Figure 1). The village Birsuat was chosen for comparison in the sources of water supply from the other administrative region.

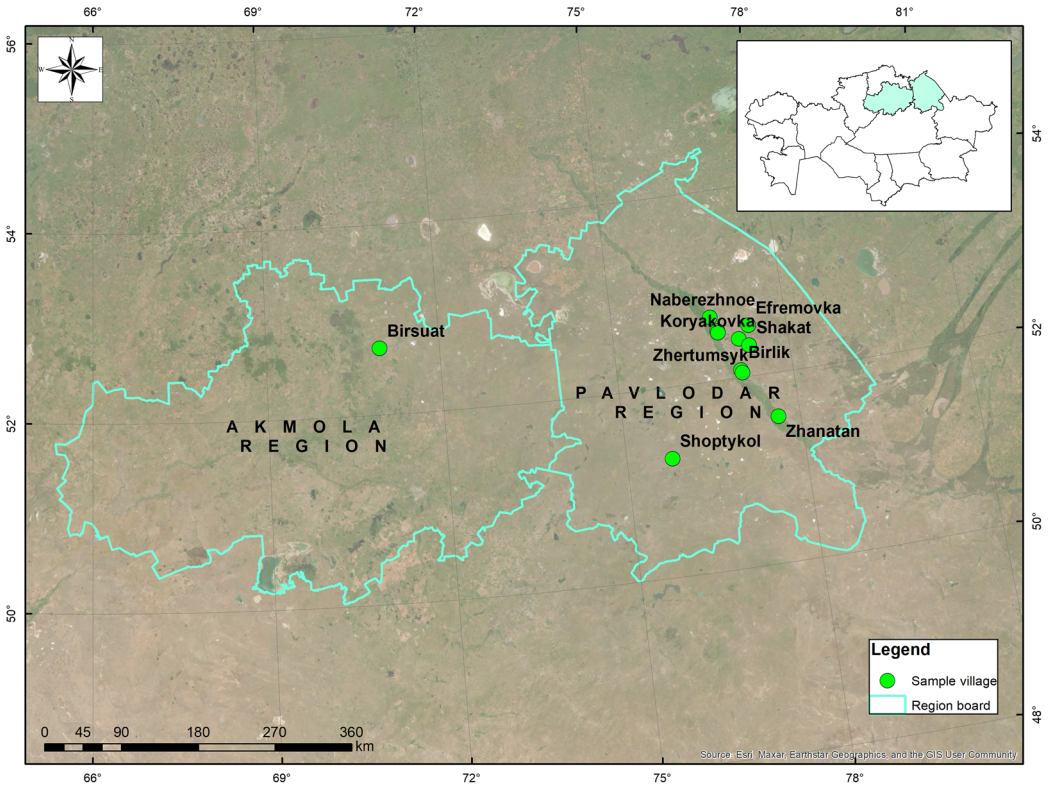


Figure 1. Research area: Location of the 10 drinking water sample villages in the Pavlodar region of northeast Kazakhstan; Location of the water sample village Birsuat in the Akmola region of north Kazakhstan. To create a map of the study area, the ArcGIS software platform version 10.4 was used. Base map source: Esri, Maxar, Earthstar Geographics, and the GIS User Community. The maps show the administrative boundaries of the Akmola region and the location of the village of Birsuat, where sampling took place [14].

The population of our research area of eleven villages in the Pavlodar and Akmola regions was 7469 individuals, but villages differ with populations ranging from 187 in Soptykol to 3058 in Birsuat (Table 1). In the research area, population was surveyed by a questionnaire that has four different types of questions. In Pavlodar and Akmola rural areas, 485 respondents were surveyed from eleven villages. From the entire population of 9810 people, 485 households of 2115 people were randomly selected to sample every fourth household of the population as respondents. Geographically, they also vary, but most of both regions' landscape is steppe. The main economic sphere is agro-industrial complex in these areas. The people mainly grow wheat, and our villages lie closer to the floodplain of the Irtysh River in Pavlodar area and the Ishim in the Akmola region.

The Pavlodar region is located in the northeast of the Republic of Kazakhstan. It borders the Omsk region in the north, the Novosibirsk region in the northeast, the Altai Territory of the Russian Federation in the east, the Abay and Karaganda regions in the south, Akmola and North Kazakhstan regions of the Republic of Kazakhstan in the west [15]. The territory of the Pavlodar region, like the territories of other regions of Northern Kazakhstan, belongs to the West Siberian climatic region of the temperate zone with a sharply continental climate. It is characterized by cold, long winters (5.5 months), hot and short summers (3 months) [15]. Most of the region is located within the southern West Siberian Plain, which is the largest plain on the globe. The relief of the southwestern part of the region is very interesting. Among the yellow–brown semi-desert steppe and small hills, with sparse vegetation, a small mountain forest oasis can be observed [16]. More than 140 rivers flow through the region. The only large river, Irtysh, flows from the south-east to the north-west for about 500 km and has several oxbow channels and islands. The rivers Tundyk, Aschisu, Shiderty, Olenty (Olenti) and others begin in the small hills, but do not

reach Irtysh and end in drainless lakes. The Irtysh–Karaganda canal was built from Irtysh, on which several dams and reservoirs were built. There are many lakes in the region, mainly salty: Seletyteniz, Kyzylkak, Zhalauly, Shureksor, Karasor, Zhamantuz, Kalkaman, etc., on the left bank; Maraldy, Moildy, Bolshoi Azhbulat, etc., on the right bank. There are 1200 small lakes in the Pavlodar region. About a hundred of them are freshwater, and the rest are saltwater. Eleven groundwater deposits with operational reserves of 3.8 million cubic meters per day have been explored in the region. All are suitable for drinking and irrigation [17]. In the Irtysh valley, there are cereal–forb and floodplain meadows, flooded hayfields and ribbon forests. Around the lakes and in the valleys of drying up rivers there are grass–sedge meadows and reed thickets. In the southern part of the left bank of Irtysh, there are fescue–wormwood and wormwood–hodgepodge semi-deserts on light chestnut soils with patches of solonetzes and solonchaks used for pastures; on the sandy areas of the right bank there are ribbon pine forests [18]. The Pavlodar region is subject to high technogenic pollution, since the basic industries are mining, oil refining, chemical industry, ferrous and non-ferrous metallurgy, and energy. The main sources of pollution are thermal power plants that use the technology of burning high-ash Ekibastuz coal in the furnaces of boiler units. The bulk of emissions comes from industrial enterprises located in the cities of Ekibastuz (46%), Aksu (26.5%), and Pavlodar (25.5%), and all other districts of the region account for only about 2% of emissions [19].

The Karaganda region (Kazakh: Karaganda oblysy/Qarağandy oblysy) is a region in the central part of Kazakhstan. The climate is sharply continental and extremely dry. The region occupies the most elevated part of the Kazakh small hills—-Saryarka. The climate is continental, winters are cold, and in some years severe, with snowstorms. Average temperatures in January are −16–−17 °C. Summer is hot, dry and windy. Average temperatures in July are 20–21 °C. The annual precipitation in the north of the region is 250–300 mm, in the south—150–210 mm, in low mountainous areas—300–400 mm. Rainfall mainly occurs from April to October [20].

The Nura River, which originates from the Balkhash–Irtysh watershed and flows into Lake Tengiz, and its tributaries, particularly the Sherubaynura, are of great economic importance. The Kulanotpes River, which also flows into Lake Tengiz, is also of economic importance. Along with this, the rivers of the Lake Karasor basin, as well as Ishim, Shiderty and other tributaries of Irtysh, are also important. The rivers of the Karaganda region are predominantly low water. There are 1910 lakes in the region, with a total area of 926 km^2. The water level in most lakes rises sharply in the spring and falls in the summer, and because of this characteristic salt marshes—sors—form along the shores by autumn. The largest lake is Balkhash. In the steppe belt, wormwood, fescue, feather grass, yellow clover, bluegrass, biurgun, and thyme grow; on flat lands acacia, spirea, rose hips are found. Fescue, feather grass, and other grasses and ephemerals grow in the semi-desert zone of the region. Sagebrush predominates on rocky hillsides. Various shrubs grow in the inter-hill depressions; birch and alder grow in the Ulytau, Karagash, and Bektau-Ata mountains; wormwood and various saltworts grow in the desert of the southern part of the region [20]. The basic sectors of the economy include electric power, fuel, ferrous metallurgy, mechanical engineering, and the chemical industry.

The samples were preserved according to standard protocols to maintain sample viability for accurate laboratory analysis. Samples were stored at a temperature of 4 °C to safeguard against degradation before analysis [22]. In field study, water samples from each village from five houses around the perimeter of the village were collected. Water samples were collected from a total of 55 households from eleven villages; sampling was repeated 3 times. A survey of residents and water samples was taken during the months of July–August 2021. The study's analytical phase incorporated a variety of standard protocols to evaluate a range of physical and chemical parameters of the water samples. The utilization of a 2100P moving turbidimeter for on-site turbidity measurements and a moving multimeter for determining pH and total dissolved solids exemplifies the application of precise and reliable instruments in field conditions. Further laboratory

analysis included the measurement of anions using a photo colorimeter among other physicochemical parameters, adhering to standardized methods to ensure consistency and accuracy in the results obtained.

Table 1. General information of the research Pavlodar and Akmola rural areas with geographical and administration features.

Name of Village	Population [1]	Geographical and Administrative Location
Gosplemstancya	1308	Part of the Michurinsky rural district
Chernoyarka	653	It is part of the Chernoyarsk rural district.
Naberezhnoe	1552	Administrative center of the Grigorievsky rural district.
Zhanatan	352	Part of the Zhambyl rural district
Zhertumsyk	234	It is part of the Zarinsky rural district.
Birlik	426	Located approximately 38 km north of the district center, the village of Bayanaul.
Koryakovka	176	Approximately 17 km northeast of Pavlodar on the shore of the Koryakovka Lake.
Shakat	774	Administrative center of the Shakatsky rural district.
Efremovka	1090	Administrative center of the Efremovsky rural district.
Shoptykol	187	60 km north of Bayanaul and 160 km northwest of Pavlodar.
Birsuat	3058	The village is located near the lake, in the central part of the region, at approximately 18 km (as the crow flies) southeast of the administrative center of the region—the city of Stepnyak.

[1] Population of villages was taken from official site of the Committee on Statistics of the Bureau of National statistics Agency for Strategic planning and reforms of the Republic of Kazakhstan [21].

2.2. Chemical Analysis of Drinking Water Samples

The methodological approach combining rigorous field sampling with detailed laboratory analysis offers a robust framework for assessing drinking water quality in the rural Pavlodar and Akmola regions. Water samples were analyzed in the chemical laboratory of L.N. Gumilyov Eurasian National University and in the Laboratory "Azimut" Karaganda with analytical methods of determination. The main chemical substances observed in this drinking water were cations (natrium and kalium, magnesium, iron, calcium) and anions (carbonates, bicarbonates, chlorides, sulfates, and nitrates), general hardness, mineralization, pH, smell, color, and turbidity. A concentration of manganese (mg/dm^3) was detected as a soil pollutant in this area [23]. The comparative analysis of the average values of these physical and chemical parameters against the Sanitary Norms of the Republic of Kazakhstan (SN of RK) drinking water standards provided a comprehensive evaluation of water quality (Table 2). Additionally, the investigation of correlations between the tested parameters provided deeper insights into the water quality dynamics and potential health implications for the local population.

Table 2. Drinking water sanitary norm of the chemical substances of Kazakhstan [22].

Hydro-Chemical Composition	Drinking Water Maximum Permissible Concentration	Hydro-Chemical Composition	Drinking Water Maximum Permissible Concentration
Chlorides, mg/L	350	Dry residue mg/L	1000 (1500)
Phosphates, mg/L	3.5	pH	6–9
Hydro carbonates	30–400	Mineralization, mg/L	1000 (1500)
Carbonates, mg/L		Iron, mg/L	0.3
Nitrates, mg/L	45	Carbonates hardness, meq/L	7 (10)
Sulfates, mg/L	500	Calcium, mg/L	
Total anions		Magnesium, mg/L	
Color, °	20 (35)	Natrium, mg/L, Kalium, mg/L	200
Manganese, mg/L	0.1 (0.5)	Total cations	

The quality of drinking water is one of the most important aspects of ensuring public health. Various countries have standards that determine the safety of water for consumption. These standards are based on scientific research and recommendations from

international organizations such as the World Health Organization (WHO). Drinking water quality analysis includes a comprehensive study of microbiological, chemical, and physical characteristics. These parameters allow us to assess the safety of water for human consumption and compliance with current regulations. Chemical indicators characterize the chemical composition of water. These indicators include water pH, hardness and alkalinity, mineralization (dry residue), anionic and cationic composition (inorganic substances), and content of organic substances. In rural areas, water standards are not always regulated since the main source is decentralized water supplies. Therefore, the main chemical indicators were chosen for research.

2.3. WQI Index Calculation

For the total assessment of water quality, the WQI was calculated using the expression given in Equation [24].

$$\mathrm{WQI} = \sum \mathrm{qn} \times \mathrm{Wn} / \sum \mathrm{Wn}, \quad (1)$$

where qn = quality rating of nth water quality parameter, Wn = unit weight of the n^{th} water quality parameter [24].

$$\mathrm{qn} = [(\mathrm{Vn} - \mathrm{Vid}) / (\mathrm{S_n} - \mathrm{Vid})] * 100, \quad (2)$$

where V_n= estimated value of the nth water quality parameter at a given sample location.

V_{id}= ideal value for the nth parameter in pure water (V_{id} for pH = 7 and 0 for all other parameters); S_n = standard permissible value of the n^{th} water quality parameter [24].

$$\mathrm{Wn} = \mathrm{k} / \mathrm{S_n}, \quad (3)$$

where S_n = standard permissible value of the n^{th} water quality parameter; k = constant of proportionality calculated using the expression given in Equation (4) [24].

$$\mathrm{k} = \left[1 / \left(1 / \sum \mathrm{S_n} = 1, 2, \ldots \mathrm{n}\right)\right] \quad (4)$$

WQI and corresponding water quality status by Horton has five types and they are described in the Table 3.

Table 3. WQI and corresponding water quality status by Horton.

N	WQI	Status	Possible Usages
1	0–25	Excellent	Drinking, Irrigation and Industrial
2	26–50	Good	Domestic, Irrigation and Industrial
3	51–75	Fair	Irrigation and Industrial
4	76–100	Poor	Irrigation
5	101–150	Very Poor	Restricted use for Irrigation
6	Above 150	Unfit for Drinking	Proper treatment required before use

2.4. Statistical Methods

All results are presented as means. Statistical analysis was conducted using analysis of variance (one-way ANOVA). Significance test of the probability level was carried out on all data. Differences were considered significant at $p < 0.05$. Since the data had a normal distribution (Kolmogorov–Smirnov test), one-way analysis of variance (ANOVA), with Tukey's post hoc test was used to identify significant differences ($p < 0.05$) between the different sources and chemical parameters and between those with or without the presence of CAF. Statistical analysis of questionnaire data for categorical variables involved determining frequency distributions and proportions in a contingency table. A chi-square test of independence was conducted to examine the relationship between categorical variables from the questionnaire and between categorical questionnaire variables and numerical variables of chemicals. Spearman's Rank correlation matrix was computed to assess the relationship between variables. The

R studio and Python3 software were used for statistical and visualization processes of all the experimental data. For statistical analysis of numerical data of chemical substances of drinking water, the next packages of R studio software (RStudio-2024-04.2-764) were used: "ggplot2", "dplyr", "tidyr", "tidyverse", "Matrix", "carData", "emmeans", "mvtnorm", "survival", "TH.data". For analysis of categorical data of the questionnaire and the correlation matrix between categorical and numerical data, the contingency table of categorical data Python software packages (matplotlib.pyplot as plt, scipy.stats as stats, seaborn as sns, networkx as nx, numpy as np, ternary, matplotlib.gridspec, GridSpec, matplotlib.lines, Line2D, matplotlib.patches, Polygon) were used.

3. Results

3.1. Statistical Data of Residents of Pavlodar and Akmola Regions

The distribution of respondents' ages across the villages varied. In the Pavlodar region, surveyed respondents' age varied from 19 to 86, and in Birsuat village of the Akmola region it ranged from 22 to 85 (Figures 2 and 3). In both regions, the main age group of respondents was 40 to 67 years old. In terms of gender, in Akmola's Birsuat village, women were slightly more predominant than men (47.5% men and 52.5% women) (Figure 3b). In the Pavlodar region, the gender composition included significantly more women (67.5%) than men (32.5%) (Figure 4). This difference of the gender composition is explained by the fact that in recent decades, a lot of young people in large cities migrate from rural areas. This is mainly due to a lack workplaces and opportunities to study at universities. The old generation usually remains in the village, and the gender component of the older generation is shifted towards women due to the longer life expectancy of women in Kazakhstan than men [25].

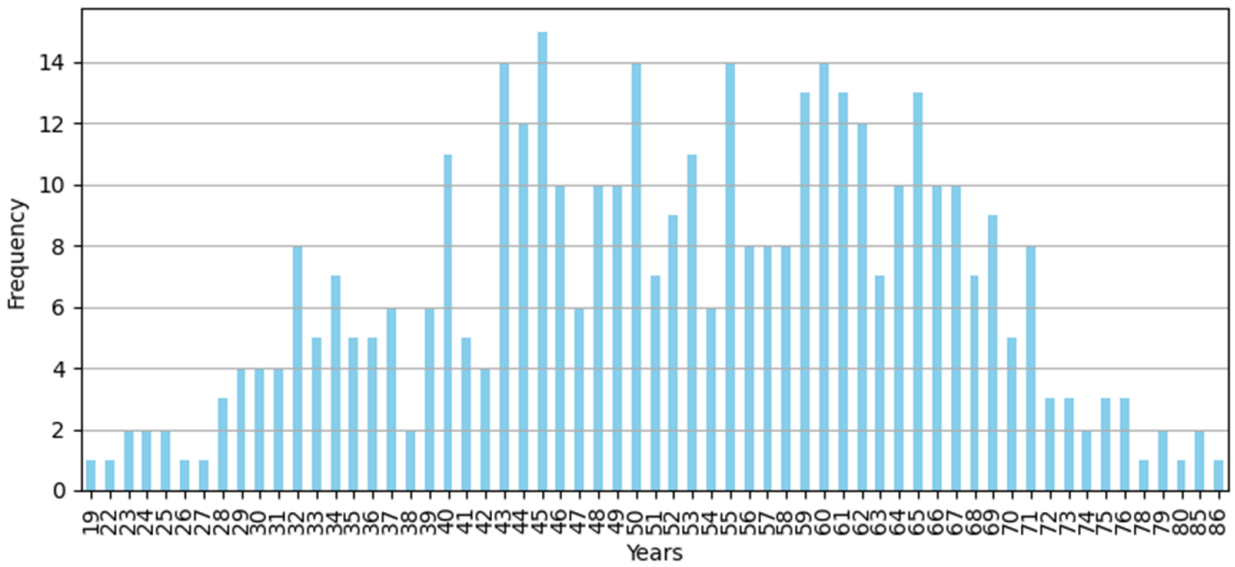
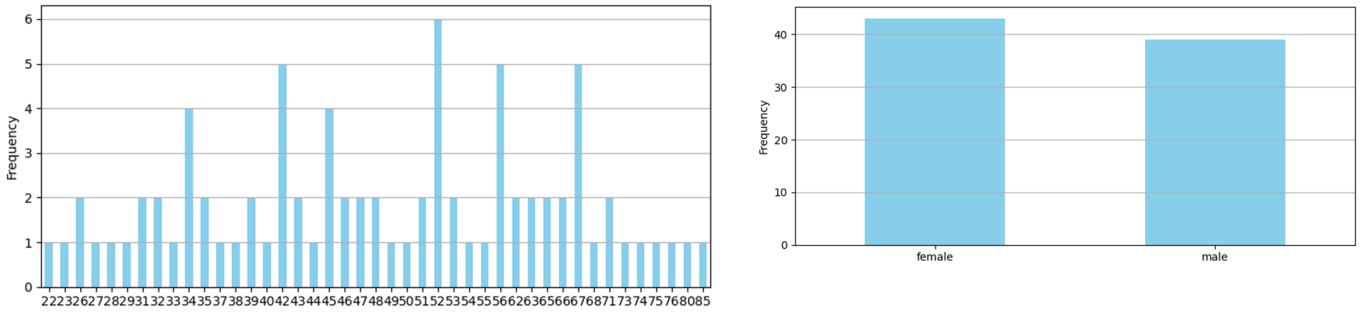


Figure 2. Distribution of population age of respondents in rural Pavlodar area. Note: *x* axis is respondents' ages, *y* axis is frequency.

More than half of the respondents in the Pavlodar region have lived in the area for more than 20 years, one-fourth have lived 11–20 years, 8% have lived from 5 to 10 years, and 8% up to 5 years. Of the respondents, 62% have garden farms, while 8% do not have farms, and 30% have livestock farms. The distribution of the number of people in a family showed that most families have 5 family members; the numbers of people with 3–4 and 6 members are also significant, while 7–10 members in a family are rare (Figure 4).



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

Figure 3. Distribution of population age (**a**) and gender (**b**) of respondents in rural Akmola area (village Birsuat). Note: (**a**) *x* axis is respondents' ages in years, *y* axis is frequency; (**b**) *x* axis is respondents' genders, *y* axis is frequency.

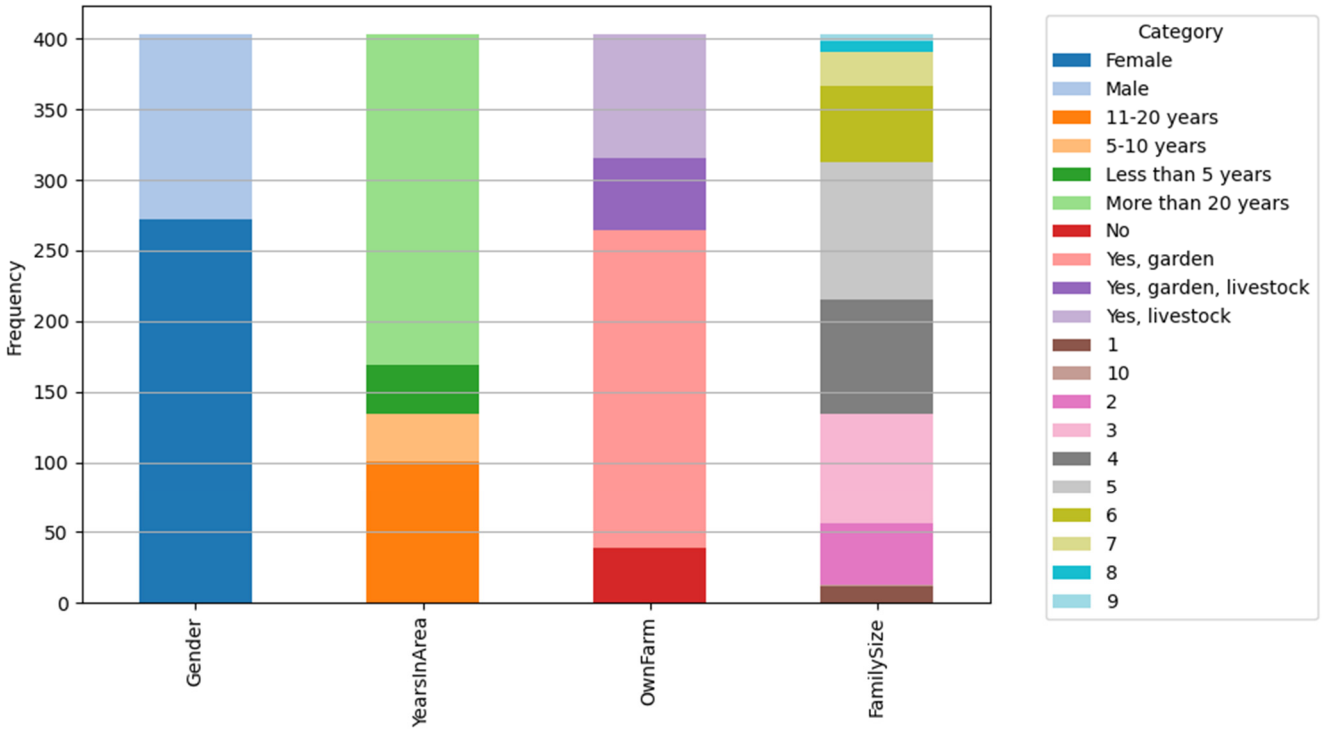


Figure 4. Distribution of general parameters of respondents in rural Pavlodar area. Note: *y* axis is frequency of categorical variables: *x* axis are categorical variables: Gender: male, female; Years in Area (length of living in area): Less than 5 years, 5–10 years, 11–20 years, More than 20 years; Own Farm (presence of household farm in the house): No, Yes, livestock, Yes, garden; Family Size—number of people in the family.

For domestic use in the Pavlodar area, almost half of the respondents use a central water supply system (48%), while 36% use both private wells without (18%) and with (18%) water supply to the house, 7% use private boreholes without water supply to the house, 9% use other types of water sources (Figure 5). The distribution of drinking water supply sources across the Pavlodar villages varied, while in Birsuat village of the Akmola region there was only one source—a well (Figures 5 and 6). 20% use private wells without water supply to the house, 7% use private boreholes without water supply to the house, 13% use public boreholes, and 7.5% use river water.

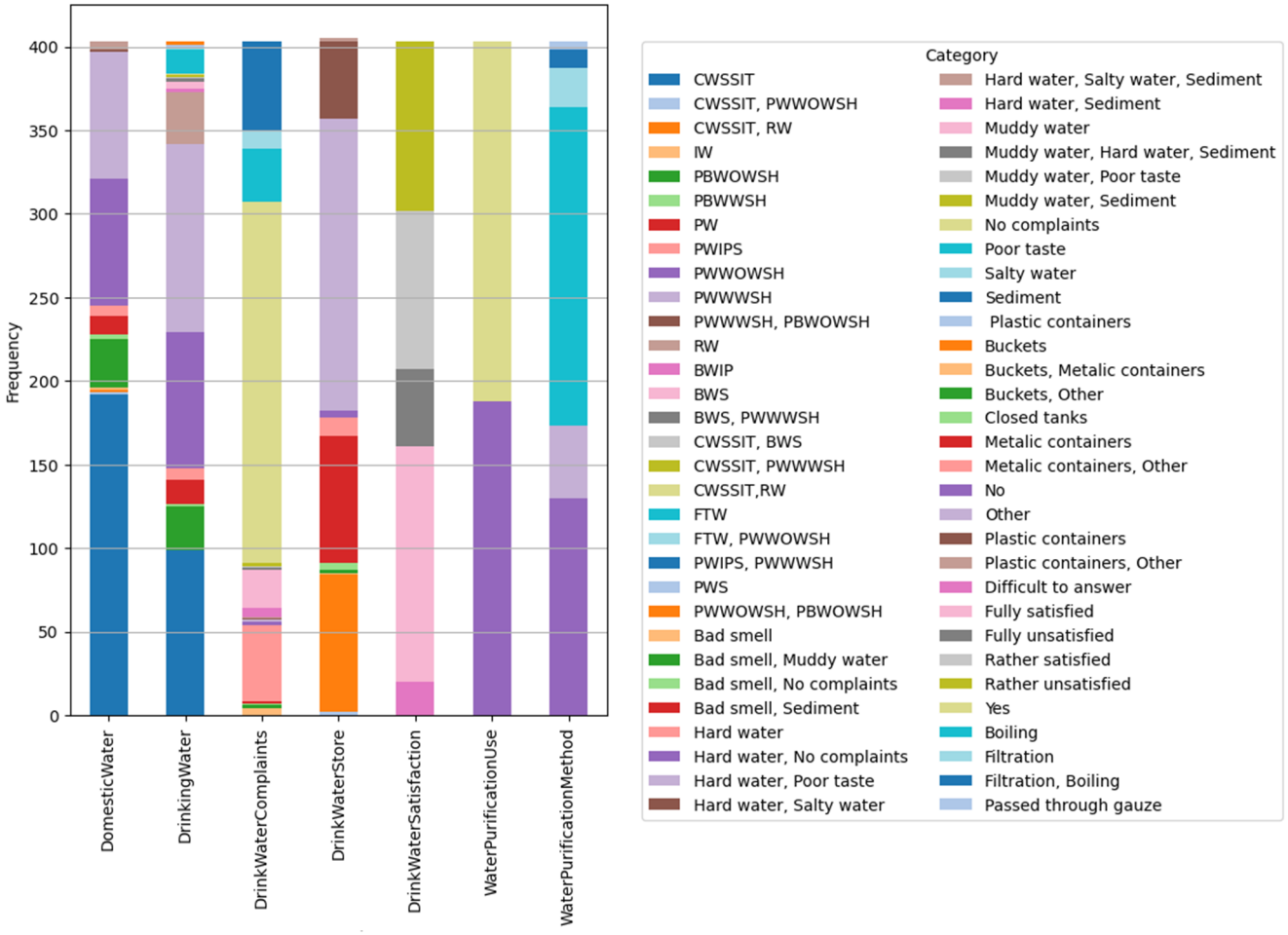


Figure 5. Distribution of water supply system and quality parameters of respondents in Pavlodar rural area. Note: *y* axis is frequency of categorical variables: *x* axis are categorical variables: Domestic Water and Drinking Water (Water sources): CWSSIT—central water supply system with inside tap, CWSSOT—central water supply system with outside tap, PWIPS—public water intake pump on the street, PWWOWSH—private well without water supply to the house, PWWWSH—private well with water supply to the house, PW—public well, PBWWSH—private borehole with water supply to the house, PBWOWSH—private borehole without water supply to the house, PB—public borehole, IW—imported water, BWS—bottled water from the stores, SW—spring water, RW—river water, BWS—bottled water from the stores, PWS—purified water from the stores, BWIP—bottled water, imported and paid for, FTW—free trucked-in water, SW—spring water; Other; Drink Water Complaints (complaints of respondents): Bad smell, Muddy water, Hard water, Salty water, Poor taste, Sediment, No complaints; Drink Water Store (where respondents store the drinking water): Closed tanks, Buckets, Plastic containers, Open tanks, Glass containers, Ceramic containers, Metallic containers, Other; Drinking Water Satisfaction (respondents' satisfaction with drinking water): Fully satisfied, Rather satisfied, Rather unsatisfied, Fully unsatisfied, Difficult to answer; Water Purification Use: Yes—Respondents use purification, No—Respondents do not use purification; Water Purification Method: Filtration, Boiling, Passed through gauze, Other.

A minority of respondents (11.5%) use bottled water from the stores, public wells, free trucked-in water, public water intake pump on the street, public boreholes and wells, and other sources (Figure 5).

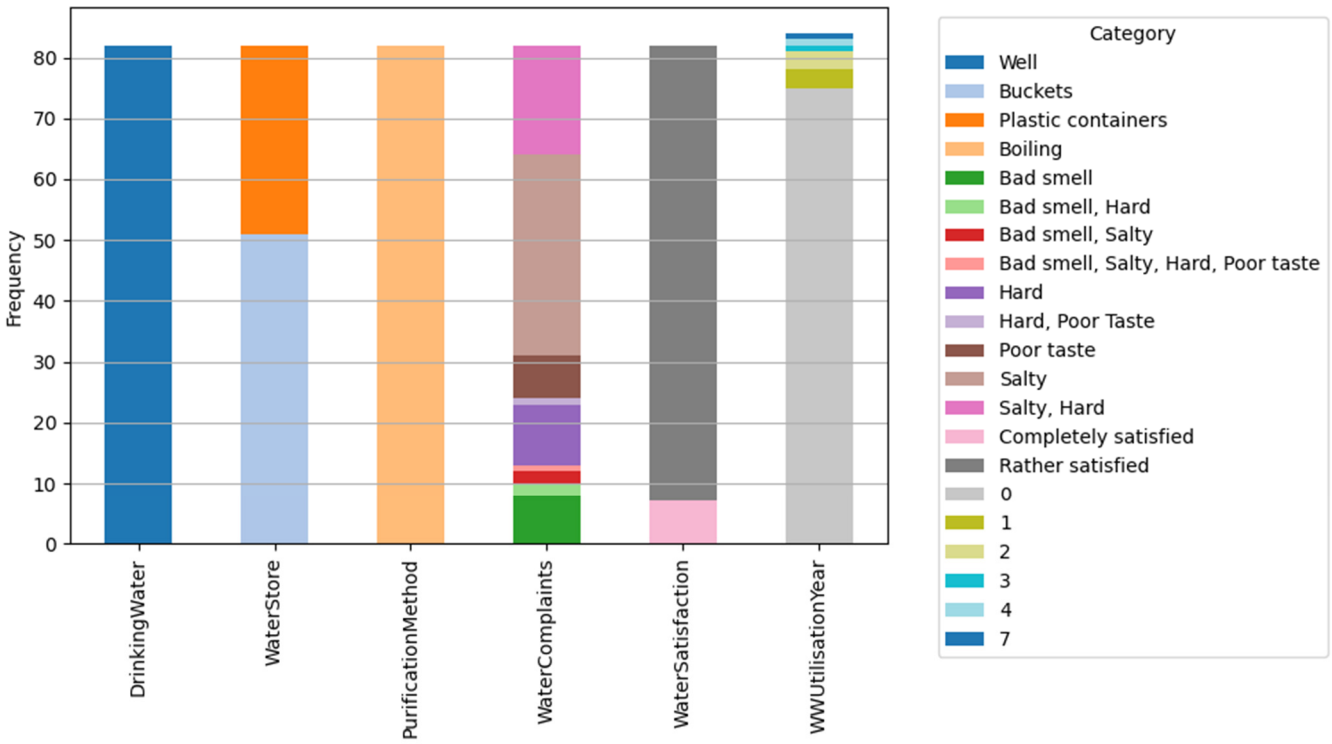


Figure 6. Distribution of water supply system and quality parameters of respondents in rural areas of Akmola. Note: *y* axis is frequency of categorical variables: *x* axis are categorical variables: Drinking Water (source): well; Water Store (were respondents save water): closed tanks, buckets, plastic containers, open containers; Purification Method—Boiling; Water Complaints (respondent complaints): Bad smell, Cloudy, Salty, Hard, Poor taste, Has sediment, Other; Water Satisfaction (respondents' satisfaction with drinking water quality): Completely satisfied, Rather satisfied, Rather unsatisfied, Completely unsatisfied; WW Utilization Year—Respondents' cleaning frequency of waste water per year.

More than half of respondents from the Pavlodar area did not complain about water quality (52%). However, 16.15% of respondents complained about sediments, 14.97% about hard water, 7.74% about bad taste, 7.14% about muddy water, 1.2% about salty water, and 0.8% about bad smell of drinking water (Figure 5). In Birsuat village of the Akmola area, half of residents complained about salty water, 29% about flat slate, 12% about bad smell, and 9% about bad taste (Figure 6).

Respondents from Pavlodar villages preferred to store water in different containers, although half of the respondents did not indicate water storage. A total of 18.55% preferred to store water in buckets, 18.07% in metallic containers, 12.55% in plastic containers, 1.15% in closed tanks, and 0.96% in open tanks. In Birsuat village, more than half of respondents (62.2%) preferred to store water in buckets, and 37.8% stored water in plastic containers (Figures 5 and 6). In the Pavlodar region, respondents' satisfaction with drinking water was distributed as follows: fully satisfied—34.24%, rather satisfied—23.07%, rather unsatisfied—24.31%, fully unsatisfied—11.16%, and difficult to answer—7.22%. In Birsuat village, most respondents (91.47%) were rather satisfied, while the remaining 8.53% were completely satisfied with drinking water quality (Figures 5 and 6). Half of the respondents in the Pavlodar region used purification methods (51%) and half did not (49%). Of those who used purification methods, 48.39% boiled their water, 30.63% did not use any purification method, 8.04% filtered water, 2.8% passed water through gauze, and the remaining used various other methods. In Birsuat village, respondents indicated only boiling as a purification method (Figures 5 and 6).

In Pavlodar villages, 73% of respondents had private toilet outside in the yard, 19.78% had toilets inside the house without access to central sewerage, and 7.22% had toilets inside the house with access to central sewerage (Figure 7). In Birsuat, all toilets were

outdoor and their location was more than 50 m away from the source of drinking water. The location of toilets with respect to drinking water source in Pavlodar villages, according to respondents, was as follows: 25.06% was more than 50 m away, 36.22% was 31–50 m away, 25% was 11–30 m away, and 11.23% was inside the house. The construction materials of toilets were reported to be wood by 76.35% of respondents, brick by 1.48%, metal by 1.23%, flat slate by 2.29%, and other materials by 3.45%. Regarding toilet utilization types, 76.22% of respondents used backfilling of cesspools, 9.27% used mechanical cleaning with fecal pumps or sewerage machine, 0.74% used chemical cleaning, and 25.9% used other methods.

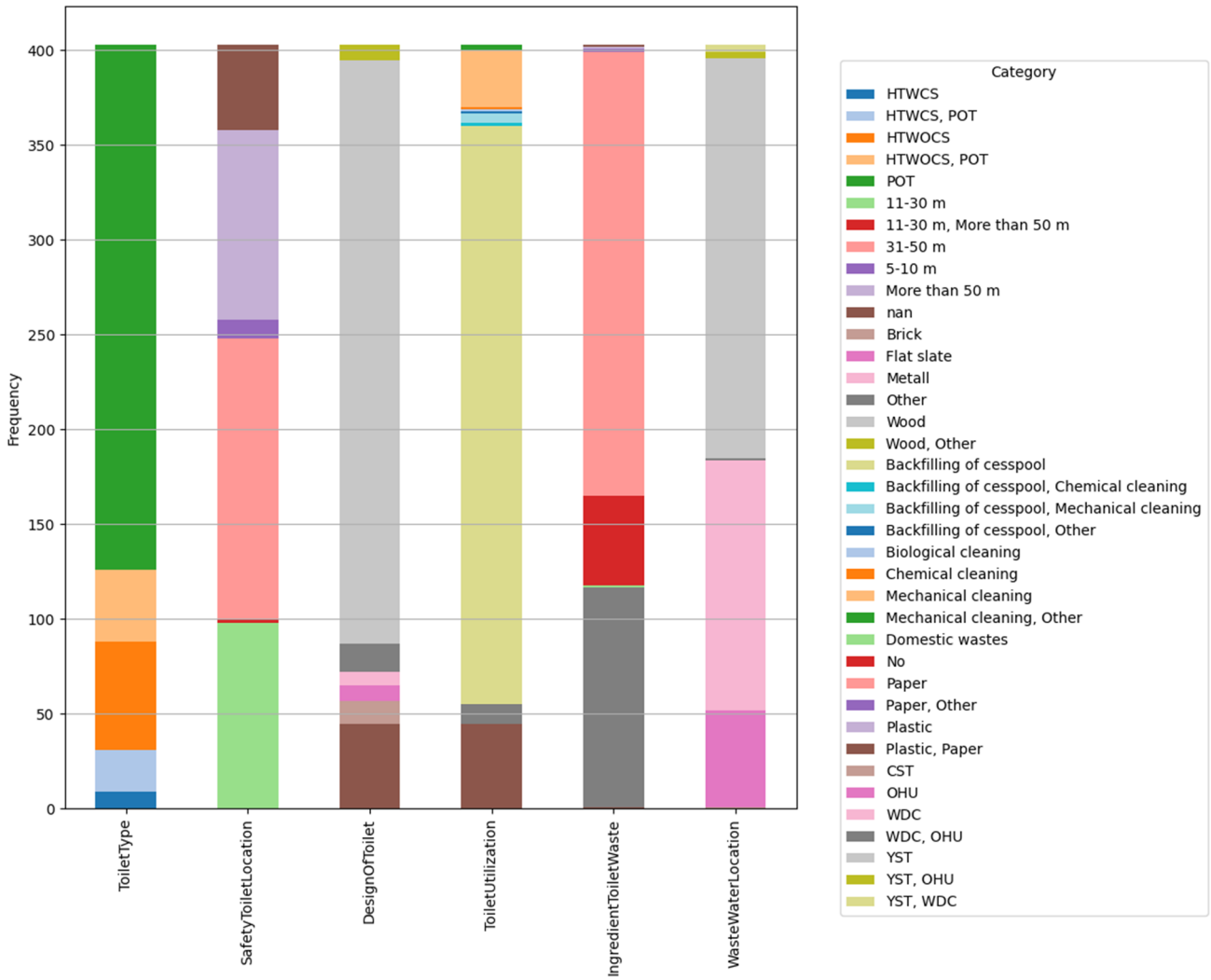


Figure 7. Distribution of sanitation parameters of respondents in rural areas of Pavlodar rural area. Note: *y* axis is frequency of categorical variables: *x* axis are categorical variables: Toilet Type: HTWCS—house toilet with access to central sewerage, HTWOCS—house toilet without access to central sewerage, POT—private outside toilet in the yard, ST—sharing toilet with neighbors; Other; Safety of Toilet Location (how far away the toilet is from drinking water source): 5–10 m, 11–30 m, 31–50 m, more than 50 m; Design of Toilet (construction of toilet): Wood, Brick, Metal, Flat slate, Plastic, Other; Toilet Utilization (type): Backfilling of cesspool, Manual cleaning, Mechanical cleaning

using fecal pumps, sewerage machine, Biological cleaning, Chemical cleaning, Other; Ingredient Toilet Waste: Plastic, Domestic wastes, Paper, Food waste, Other; Waste Water Location (where waste water flows down): CSS—centralized sewer system, YST—yard Storage tank, CST—centralized storage tank or storage tank is shared with neighbors, WDC—without designated collector, OHU—other household usage (watering the garden, for pets), 6—other.

In Birsuat village of the Akmola region, respondents indicated that the frequency of wastewater collection ranges from two to seven times per year (Figures 6 and 7). In Pavlodar villages, more than half of the respondents indicated various ingredients in the toilet waste paper: 28.54% indicated other materials and 0.49% reported plastics. The location of wastewater collectors was as follows: half of the respondents used a storage tank in the yard, less than 1% used a centralized storage tank or a shared storage tank with neighbors, 35% had no designated collection place, and 12.14% used the wastewater for other household needs, such as watering the garden or for pets (Figure 7).

In Pavlodar villages, 76.92% of respondents indicated that state representatives are responsible for both public pump and central water supply system, 22.59% indicated private companies, 82% believed the state is responsible for drinking water safety, 10.36% indicated private companies, and 7.23% believed household owners are responsible. Additionally, 99% of respondents indicated that household owners are responsible for the proper maintenance of toilets and wastewater utilization (Figure 8).

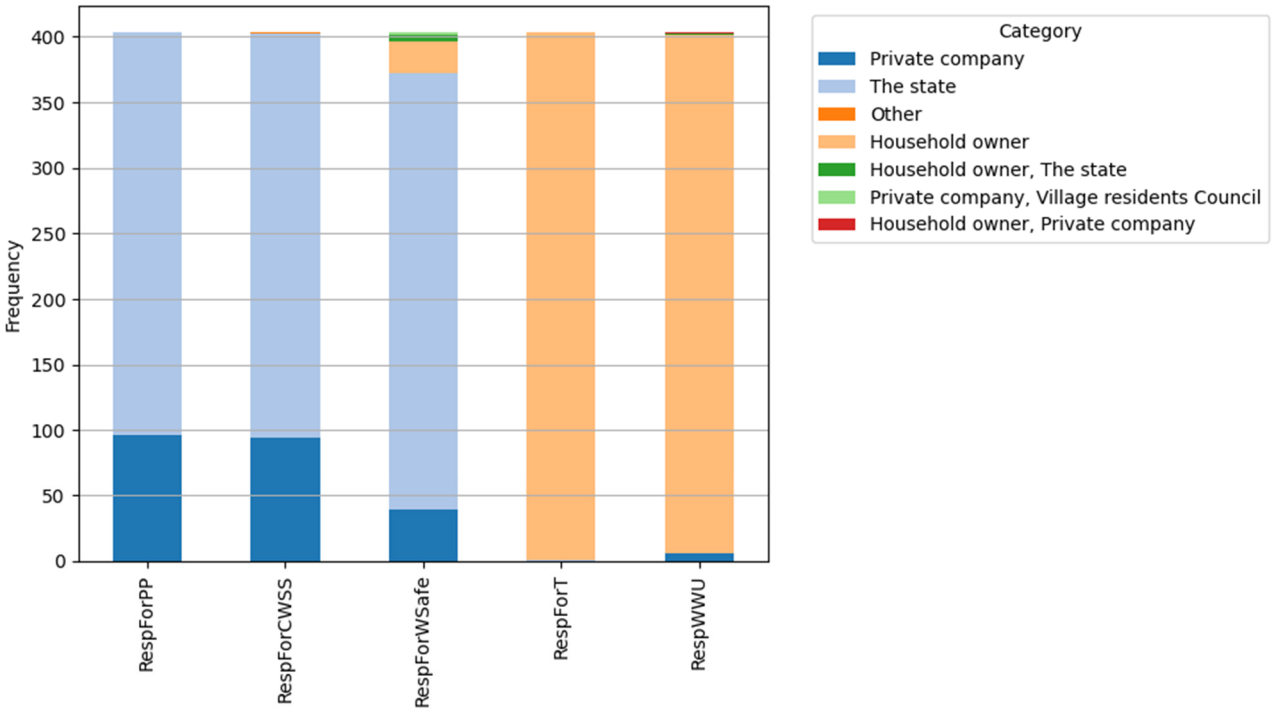


Figure 8. Distribution of responsibility parameters of respondents in rural areas of Pavlodar area. Note: y axis is frequency of categorical variables: x axis are categorical variables: Resp For PP (Responsibility for public pumps), Resp For CWSS (Responsibility for central water supply system), Resp For WSafe (Responsibility for drinking water supply safety), Resp ForT (Responsibility for proper maintenance of toilet) and Resp For WWU (Responsibility for waste water utilization): Household owner, The state, Private company, Village residents council, Other.

3.2. Perceiving Drinking Water Quality

Regarding satisfaction with drinking water, 52 respondents from Pavlodar villages are completely satisfied, 25 are rather satisfied, and 24 are rather unsatisfied with private wells water at private houses with water supply to the house. A total in 30 respondents are satisfied, 19 are satisfied, 21 are unsatisfied, and 12 are unsatisfied with private well water

in private houses without water supply to the house. For the central water supply with an inside tap water, 28 respondents are completely satisfied, 25 are rather satisfied, 31 are rather unsatisfied, and 10 are completely unsatisfied (Figure 9).

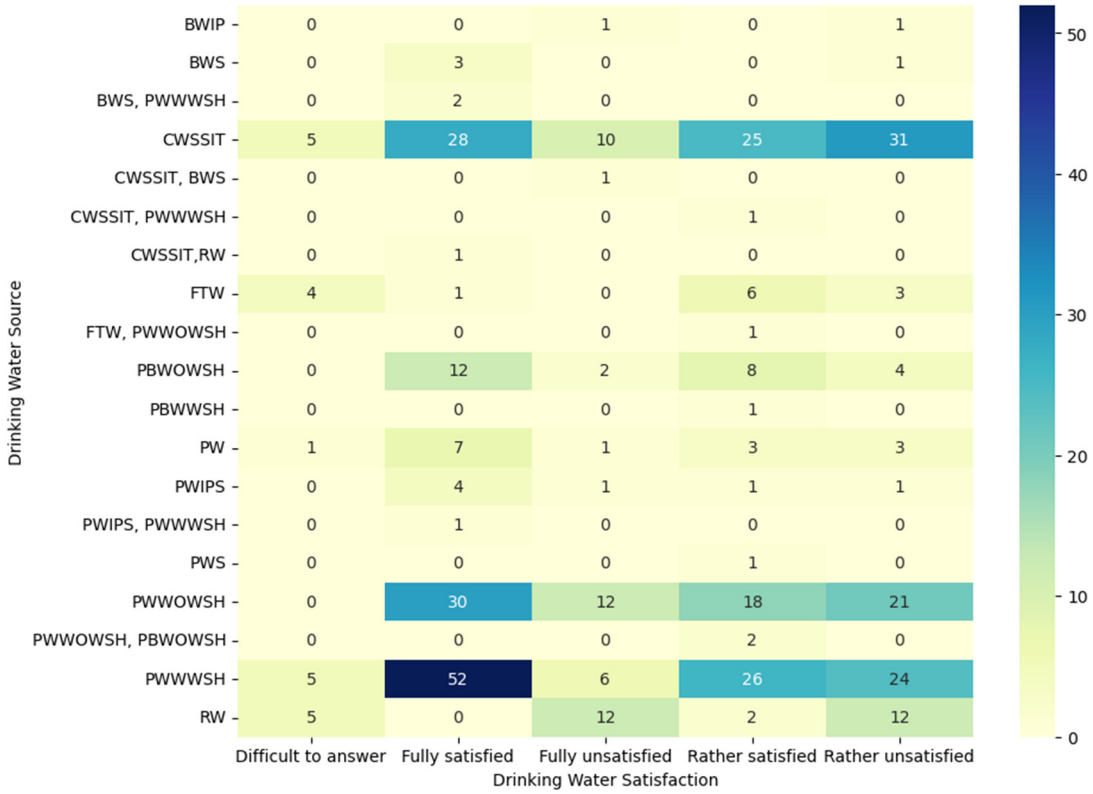


Figure 9. Cross-tabulation of drinking water source and satisfaction of respondents in rural areas of Pavlodar rural area. Note: *y* axis is Drinking Water (source): Drinking Water (Water sources): CWSSIT—central water supply system with inside tap, CWSSOT—central water supply system with outside tap, PWIPS—public water intake pump on the street, PWWOWSH—private wells without water supply to the house, PWWWSH—private wells with water supply to the house, PW—public well, PBWWSH—private borehole with water supply to the house, PBWOWSH—private borehole without water supply to the house, PB—public borehole, IW—imported water, BWS—bottled water from the stores, SW—spring water, RW—river water, BWS—bottled water from the stores, PWS—purified water from the stores, BWIP—bottled water imported and paid for, FTW—free trucked-in water, SW—spring water; Other; *x* axis is Drinking Water Satisfaction (respondents' satisfaction on drinking water): Fully satisfied, Rather satisfied, Rather unsatisfied, Fully unsatisfied, Difficult to answer.

Despite most respondents having no complaints about drinking water, there were some specific complaints. Respondents mentioned sediment in the water: 13 of central water supply system with inside tap, 12 in private wells at houses without and with water supply, 6 in private boreholes in houses without water supply, and 9 in river/lake water. Complaints about bad taste were indicated by 6–8 respondents in private wells without and with water supply, 11 in river source. A total of 22 respondents complained about hard water in the central water supply system with an inside tap, 8–7 in private wells in houses without and with water supply, 5 in public wells. In addition, muddy water was mentioned by 10 respondents regarding in river sources, by 7 in the central water supply system with an inside tap, and by 4 in private wells at houses without and with water supply (Figure 10).

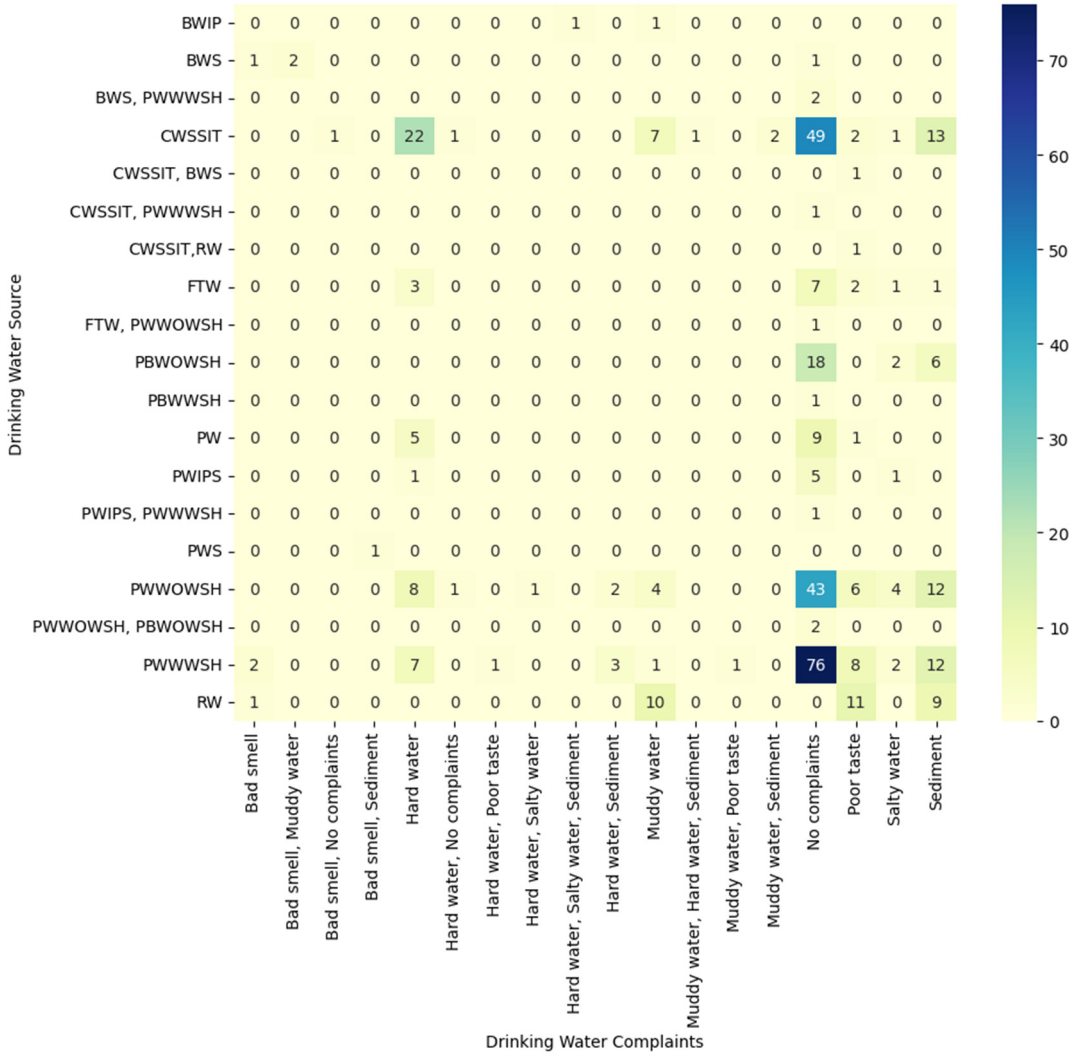


Figure 10. Cross-tabulation of drinking water source and complaints of respondents in rural areas of Pavlodar rural area. Note: *y* axis is Drinking Water (source): CWSSIT—central water supply system with inside tap, CWSSOT—central water supply system with outside tap, PWIPS—public water intake pump on the street, PWWOWSH—private well without water supply to the house, PWWWSH—private well with water supply to the house, PW—public well, PBWWSH—private borehole with water supply to the house, PBWOWSH—private borehole without water supply to the house, PB—public borehole, IW—imported water, BWS—bottled water from the stores, SW—spring water, RW—river water, BWS—bottled water from the stores, PWS—purified water from the stores, BWIP—bottled water imported and paid for, FTW—free trucked-in water, SW—spring water; Other; *x* axis is Drink Water Complaints (complaints of respondents): Bad smell, Muddy water, Hard water, Salty water, Poor taste, Sediment, No complaints.

A total of 67 respondents stated that water from the central water supply system with an inside tap was mostly purified, 38 and 41 stated that from private wells at houses without and with water supply was purified, and 29 stated that water from river source was also purified. In addition, 12 respondents indicated that water from private boreholes at houses without water supply to the house was also purified, and 9 respondents indicated that free trucked-in water was purified (Figure 11).

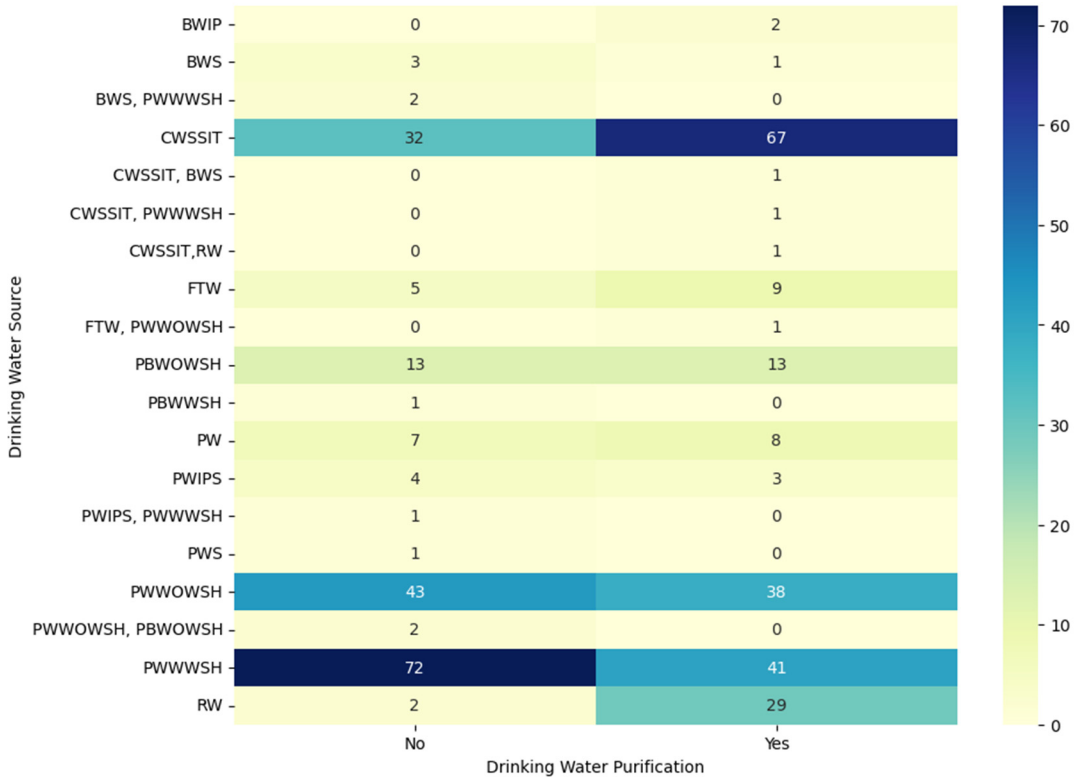


Figure 11. Cross-tabulation of drinking water source and purification of respondents in rural areas of Pavlodar rural area. Note: *y* axis is Drinking Water (source): CWSSIT—central water supply system with inside tap, CWSSOT—central water supply system with outside tap, PWIPS—public water intake pump on the street, PWWOWSH—private well without water supply to the house, PWWWSH—private well with water supply to the house, PW—public wells, PBWWSH—private borehole with water supply to the house, PBWOWSH—private borehole without water supply to the house, PB—public borehole, IW—imported water, BWS—bottled water from the stores, SW—spring water, RW—river water, BWS—bottled water from the stores, PWS—purified water from the stores, BWIP—bottled water imported and paid for, FTW—free trucked-in water, SW—spring water; Other; Water Purification Use: Yes—respondents use purification, No—respondents do not use purification.

Regarding purification methods, 175 respondents used boiling, 23 used filtration, 11 used both boiling and filtration, and 5 passed water through gauze (Figure 12). Respondents who purify water complained about bad smell (3), muddy water (18), hard water (43), salty water (9), bad taste (28), and sediment (50) (Figure 13).

Complaints about sediment correlated with the distance of toilets to drinking water sources as follows: 26 respondents with 31–50 m, 14 with 11–30 m, 8 with more than 50 m, and 5 with inside toilets. Complaints about bad taste correlated with 12 respondents with 31–50 m, 11 with more than 50 m, 7 with 11–30 m. Hard water complaints correlated with a 31–50 m distance of toilets from drinking water source in 20 respondents, inside house toilets in 10 respondents, more than 50 m in 9 respondents, and with 11–30 m in 7 respondents. Complaints about salty water also were reported by nine respondents with a distance farther than 50 m, six with 31–50 m and five with 11–30 m from the toilet to the water source (Figure 14).

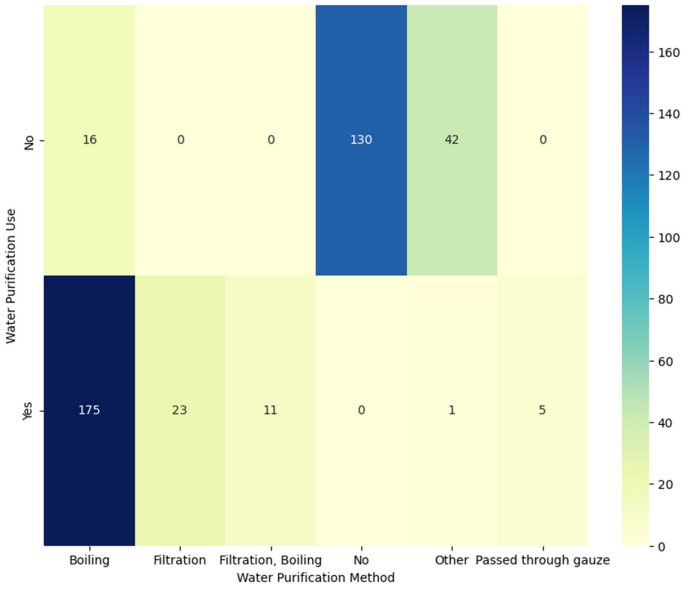


Figure 12. Cross-tabulation of drinking water purification and methods of respondents in rural areas of Pavlodar rural area. Note: *y* axis is Water Purification Use: Yes—respondents use purification, No—respondents do not use purification; *x* axis is Water Purification Method: Filtration, Boiling, Passed through gauze, Other.

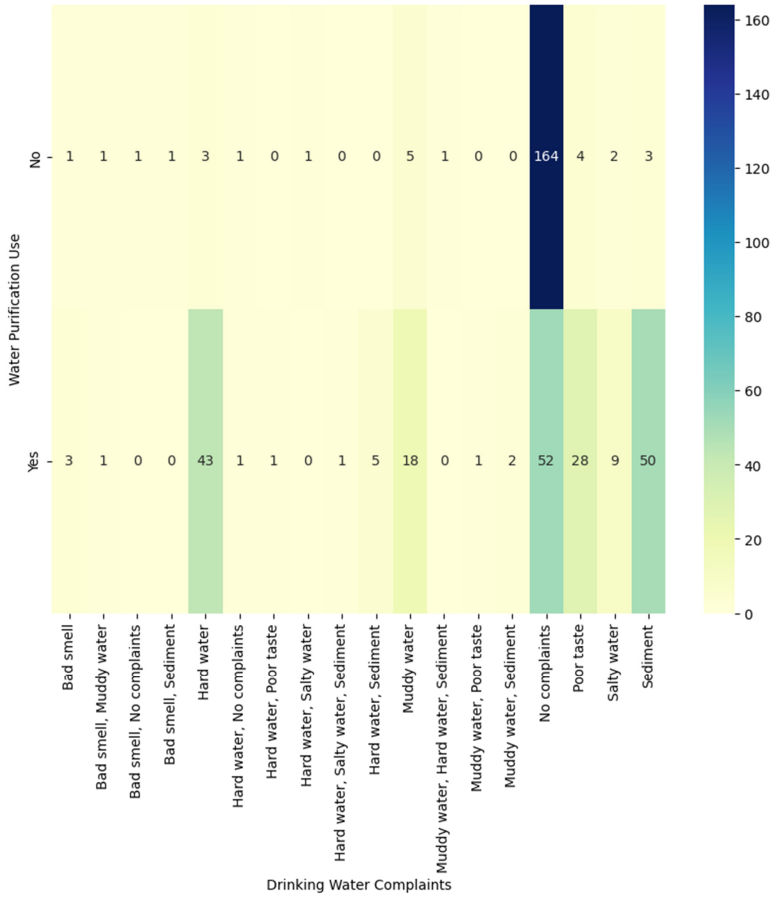


Figure 13. Cross-tabulation of drinking water purification and complaints of respondents in rural areas of Pavlodar rural area. Note: *y* axis is Water Purification Use: Yes—respondents use purification, No—respondents do not use purification; *x* axis is Drink Water Complaints (complaints of respondents): Bad smell, Muddy water, Hard water, Salty water, Poor taste, Sediment, No complaints.

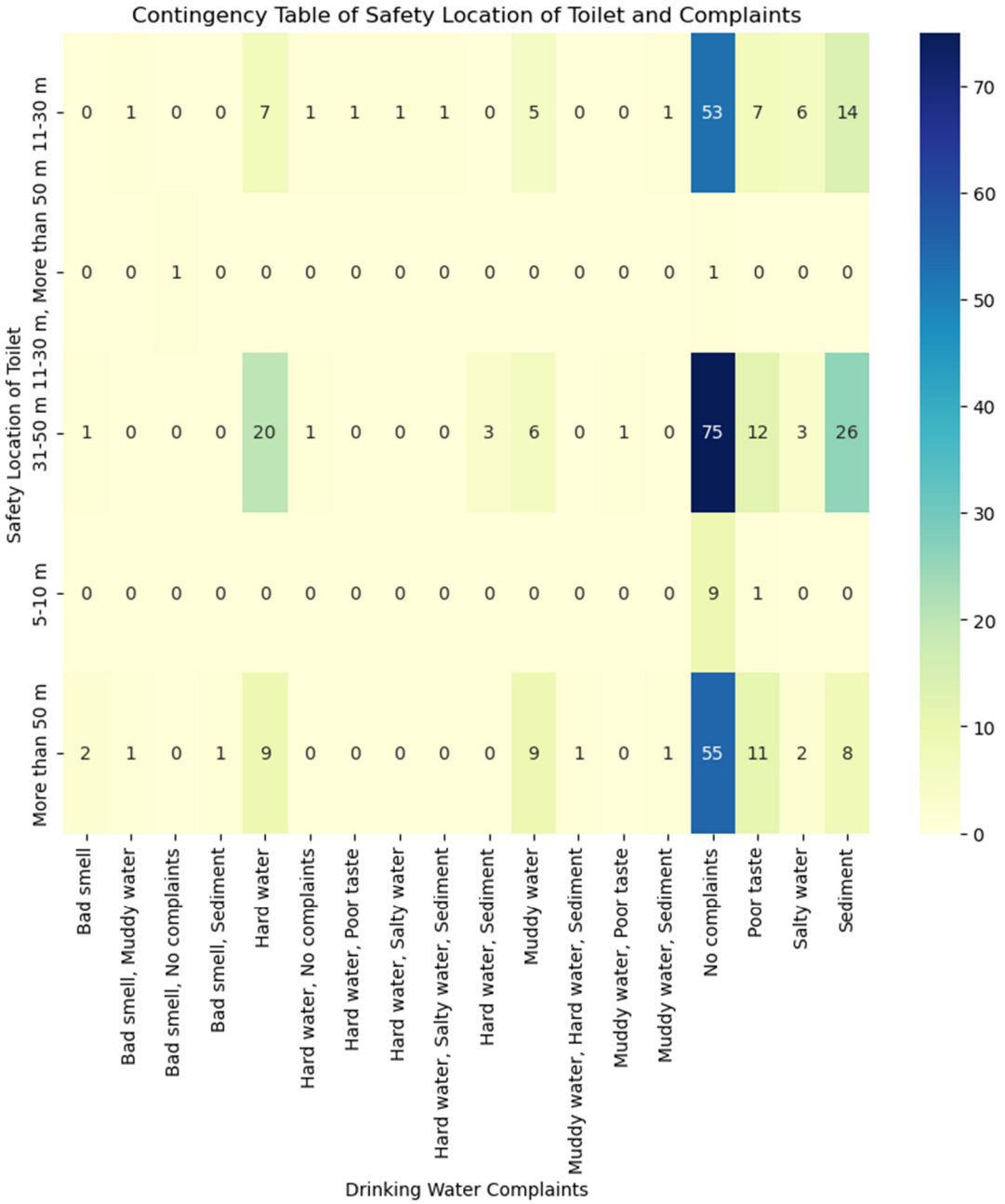


Figure 14. Cross-tabulation of Location of Toilets and complaints of respondents in Pavlodar rural area. Note: *y* axis is Safety Location of Toilet (how many meters toilet locates from drinking water source): 5–10 m, 11–30 m, 31–50 m, More than 50 m; *x* axis is Drink Water Complaints (complaints of respondents): Bad smell, Muddy water, Hard water, Salty water, Poor taste, Sediment, No complaints.

Complaints about sediment also correlated with the type of wastewater collectors: 21 respondents had no designated collection place, 17 had a storage tank in the yard, 12 used wastewater for other household needs. Hard water complaints correlated with a storage tank in the yard in 27 respondents, no designated collection place in 15 respondents, and wastewater used for other household needs in 4 respondents (Figure 15).

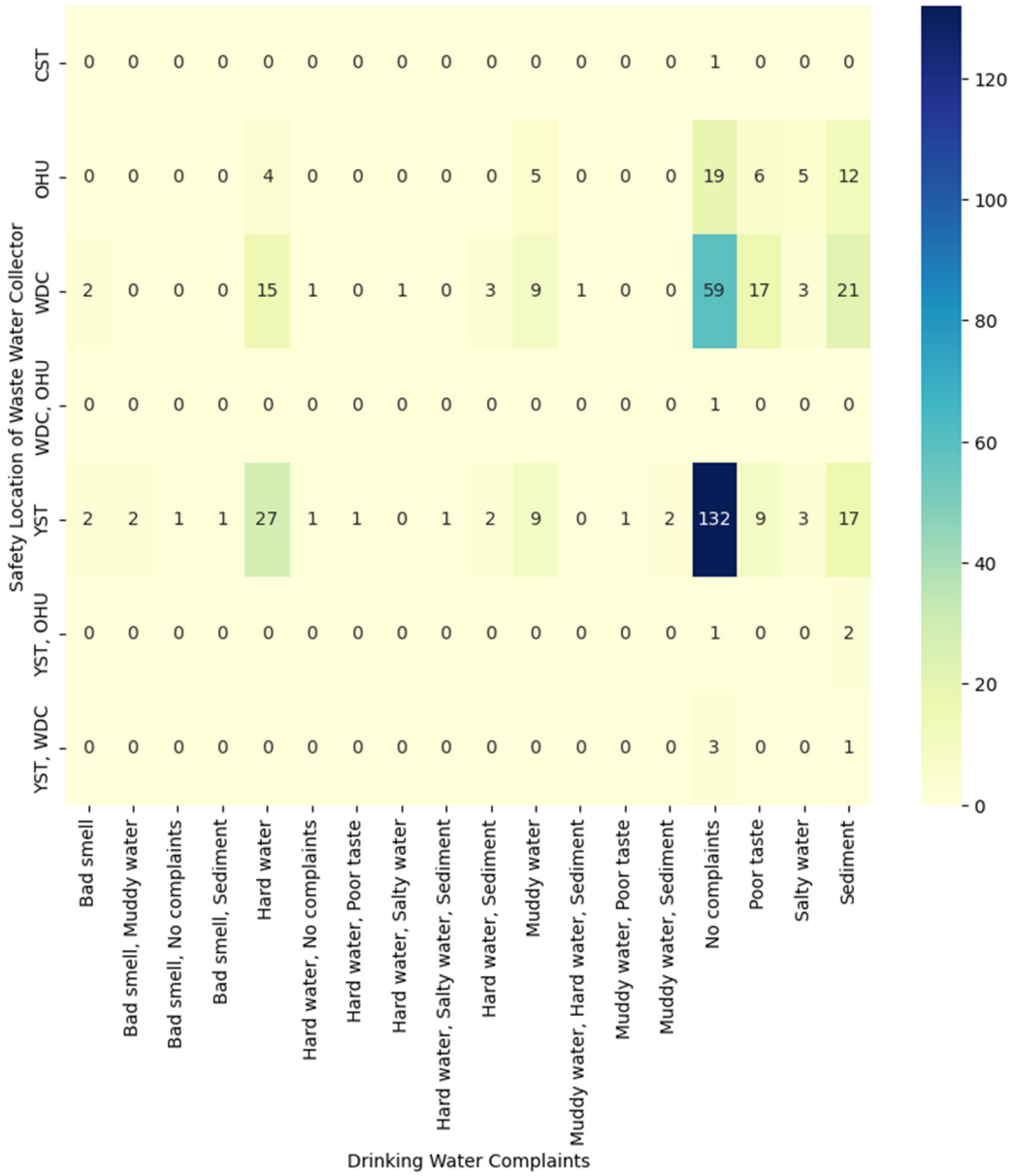


Figure 15. Cross-tabulation of sanitary Wastewater Collector Location and complaints of respondents in Pavlodar rural area. Note: *y* axis is Waste Water Location (where waste water flows down): CSS—centralized sewer system, YST—yard storage tank, CST—centralized storage tank or storage tank is shared with neighbors, WDC—without designated collector, OHU—other household usage (watering the garden, for pets), 6—other; *x* axis is Drink Water Complaints (complaints of respondents): Bad smell, Muddy water, Hard water, Salty water, Poor taste, Sediment, No complaints.

Bad taste complaints also correlated with no designated collection place (17 respondents), a storage tank in the yard (9 respondents), and use for other household needs (6 respondents). In general, the respondents' answers did not show all types of collectors, indicating that there is no centralized sewerage system in Pavlodar villages.

3.3. Hydro–Chemical Parameters of Pavlodar and Akmola Rural Area Drinking Water and Their Correlation with Perceived Quality of Water

Most water sources in Pavlodar villages do not have a dominant type of cations and anions, except for spring water, river/lake water, public wells, and Complex Block Module sources (Figure 16). Spring water and Complex Block Module sources have Na^++K^+, river sources and public wells have the Ca cation type of water, while spring water has the

CO_3 anion type water. Despite many samples having Ca^{2+}, Mg^{2+}, $SO_4{}^{2+}$ mixed type of water, the river source has Ca^{2+}, Mg^{2+}, $CO_3{}^{3+}$ type of water, and the spring water and the Complex Block Module source have Na^+, K^+, Cl^- type of water.

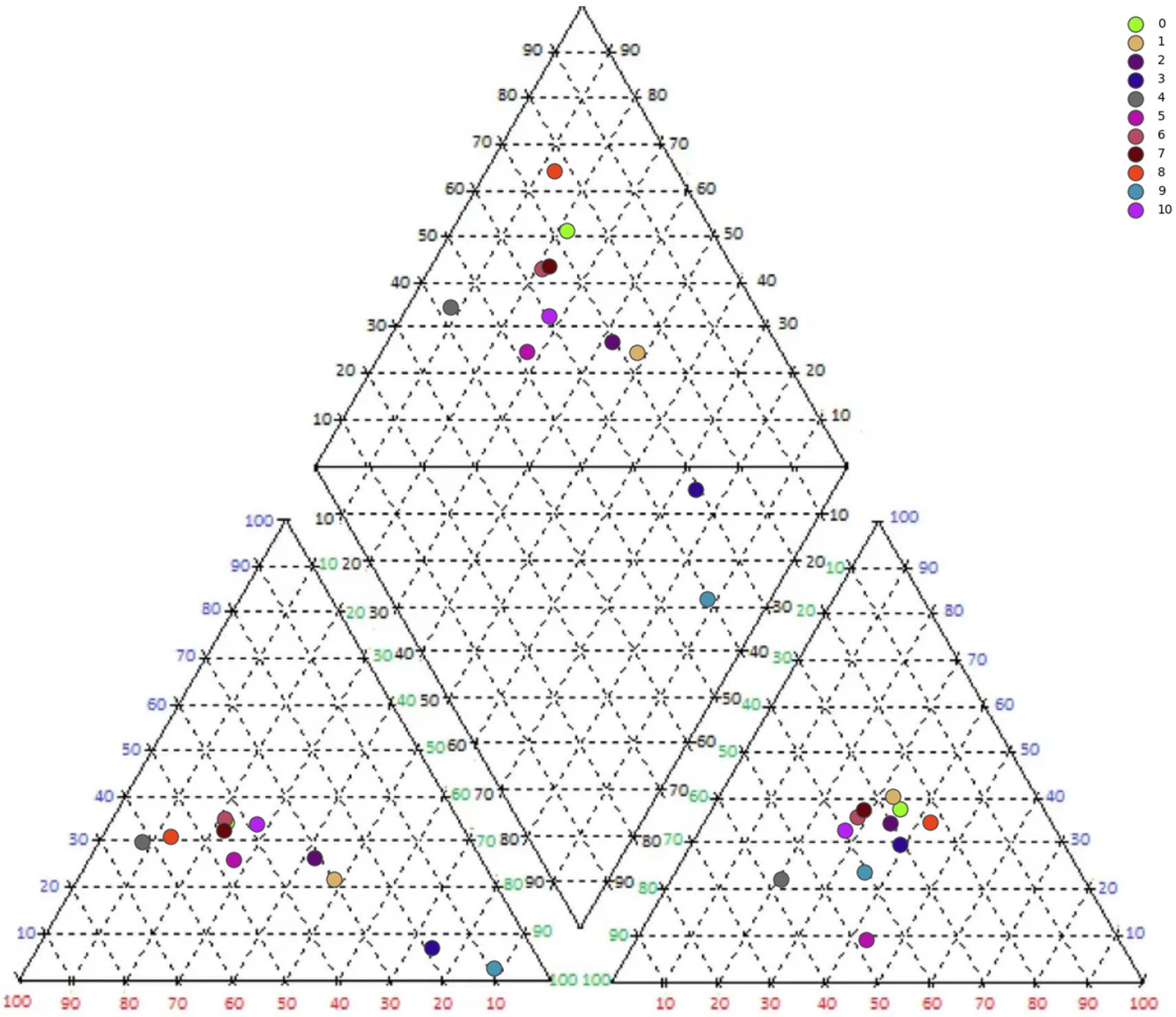


Figure 16. Piper diagram of drinking water source samples of Pavlodar rural area. the ternary plot of cations is on the left (*x* axis with red numbers—Ca^{2+}, *y* axis with blue numbers—Mg^{2+}, *z* axis with green numbers—Na^++K^+); the ternary plot on anions is on the right side (*x* axis with red numbers—Cl^-, *y* axis with blue numbers—$SO_4{}^{2+}$, *z* axis with green numbers—$HCO_3{}^{2-}$+$CO_3{}^{3-}$). Drinking water sources: 0—private wells at private houses with water supply to the house, 1—central water supply system with inside tap, 2—water tower, 3—spring water, 4—river/lake water, 5—free trucked-in water, 6—private boreholes at private houses without water supply to the house, 7—private wells at private houses without water supply to the house, 8—public wells, 9—Complex Block Module, 10—private hand well.

Calcium is the most common cation found in the rivers of the world. It is released by the weathering of sedimentary carbonate rocks and is often grouped with magnesium. In our studies, river sources and public wells have a dominant calcium cation due to this. Public wells supply water from a shallower depth than other sources. In contrast, CBM and spring water take water from deep artesian wells, where there is more sodium and potassium. Sodium is found in connection with chloride ions. Rocks containing NaCl are the most common source of sodium contained in river water. In coastal areas, Na^+- and Cl^--containing rainwater can be more widespread. Cable waters, fertilizers, and road salt are common sources of Na^+ in water. Potassium (K^+) is the least common cation in river

water. It is released from silicate minerals, such as the field spar from potassium and mica. Important factors are depth, location of the drinking water source, distance of the source from surface water, and landscape of the area.

The heatmap (Figure 17) represents the concentration of various chemical substances in drinking water samples from research villages in the Pavlodar region. Our results show that several chemical substances are outside the standards in some Pavlodar villages. Dry residue is high in Gosplemstanciya, Shakat, and Zhertumsyk. Hardness exceeds the MPC in Chernoyarka, Gosplemstanciya, Zhanatan, and Zhertumsyk. Mineralization is above the MPC in Gosplemstanciya, Shakat, Zhanatan, and Zhertumsyk. Iron cations are above the MPC in Gosplemstanciya, Na and K in Gosplemstanciya, Shakat and Shoptykol. Nitrates exceed the MPC in Chernoyarka and Zhertumsyk, manganese in Chernoyarka and Zhanatan.

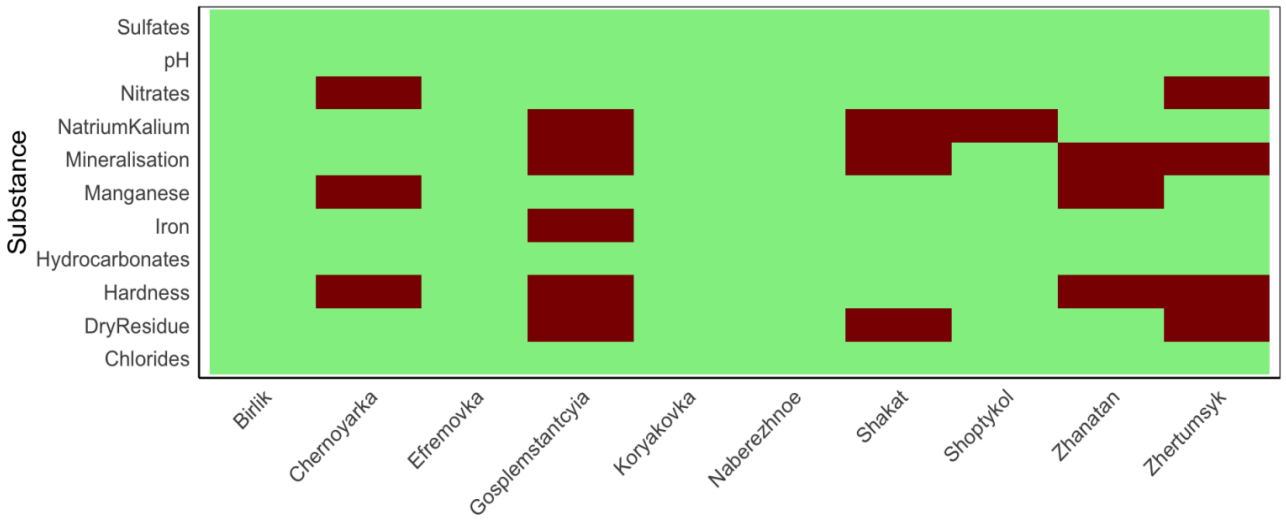


Figure 17. Chemical substances in drinking water samples of rural areas of Pavlodar region that are above the Maximum Permissible Concentration (MPC). Darker shaded areas are above the maximum, green colors are below MPC.

Based on the questionnaire data and chemical indicators, we observe strong correlations between various factors. For example, the source of drinking water has a weak relationship with pH (0.24) and complaints about bad taste (0.19). The drinking water source has a strong relationship with water purification use (0.48), toilet utilization type (0.34), and complaints about bad smell (0.39). Drinking water satisfaction weakly correlates with total microbial amounts (0.25), general hardness (0.25) and complaints about bad smell (0.36), hard water (0.43), salty water (0.64), bad taste (0.23) and sediment (0.51) (Figure 18). Responsibility for public pump correlates with responsibility for the central water supply system (0.59). Responsibility for the central water supply system correlates with responsibility for wastewater utilization type (0.41) and complaints about bad taste (0.34).

The Water Quality Index of drinking water has a strong relationship with mineralization (0.64) and general hardness (0.57). Drinking water mineralization strongly correlates with general hardness (0.79). Complaints about sediments are related to complaints about salty water (0.48), bad smell (0.43), muddy water (0.4), and hard water (0.3). Complaints about salty water have a strong relationship with complaints about bad smell (0.57) and hard water (0.43). Complaints about bad smell significantly correlate with complaints about bad taste (0.43).

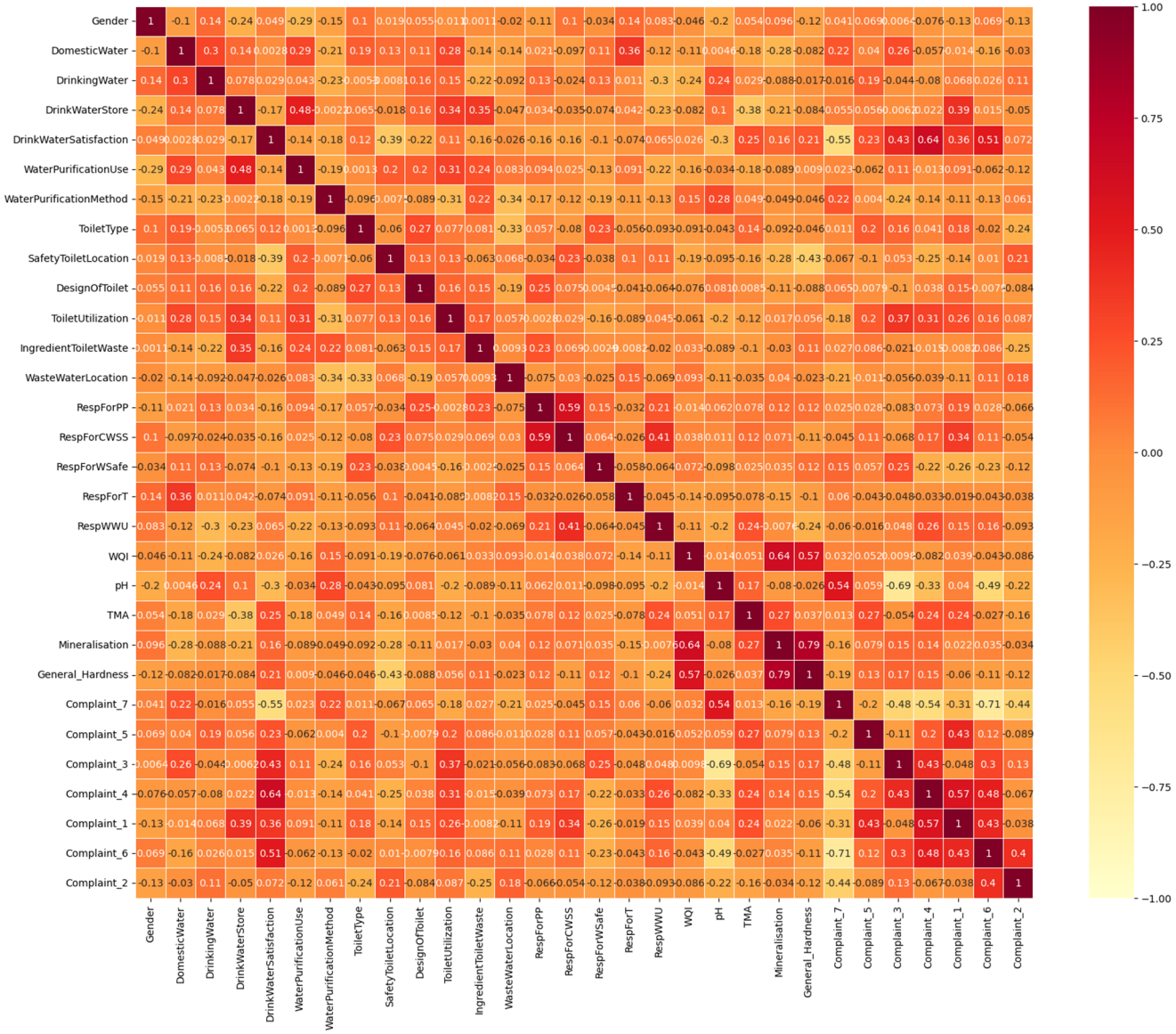


Figure 18. Correlation matrix of complaints and water source supply and sanitation conditions of respondents in Pavlodar rural area. Questionary Data: Gender, Domestic Water (type), Drinking water (source), Drink Water Store (where respondents store the drinking water), Drinking Water Satisfaction (respondents' satisfaction with drinking water), Water Purification Use, Water Purification Method, Toilet Type, Safety Toilet Location (how far away the toilet is from the drinking water source), Design of Toilet (construction of toilet), Toilet Utilization (type), Ingredient Toilet Waste, Waste Water Location (where waste water flows down), Resp For PP (responsibility for public pumps), Resp For CWSS (responsibility for central water supply system), Resp For WSafe (responsibility for drinking water supply safety), Resp ForT (responsibility for proper maintenance of toilet), Resp For WWU (responsibility for waste water utilization); Chemical parameters of drinking water: General Hardness, meq/L, TMA (total microbial amount), $*10^4$/L, pH, WQI (Water Quality Index); Complaint (complaints of respondents): 1—bad smell, 2—muddy water, 3—hard water, 4—salty water, 5—bad taste, 6—sediment, 7—no complaints.

4. Discussion

Most residents in the Pavlodar and Akmola regions have lived there for over 20 years. Most families consist of five members. The majority (48%) of respondents in the Pavlodar region rely on a central water supply system, while 36% use both private wells and the central system. In Pavlodar, 29% of respondents use water from private wells, and 25% use

central water supplies for drinking. In contrast, residents in Birsuat only have access to a well. In the Pavlodar region, 16.15% of respondents complain about hard water, 14.97% about unpleasant taste, 7.74% about cloudy water, 7.14% about salty water, and 0.8% about unpleasant odors. In Birsuat, 50% of respondents complain about salty water, 29% about flat shale, 12% about unpleasant odors, and 9% about unpleasant taste.

In terms of water source satisfaction, respondents exhibit varying levels of satisfaction with different water supply types. Satisfaction levels are higher for those with inside tap water systems (28 completely satisfied), while private wells, both with and without water supply to the house, show more mixed satisfaction levels. These findings are consistent with previous research, indicating the importance of reliable and safe water sources in rural satisfaction [26]. In the Pavlodar region, 34.24% of respondents are completely satisfied with their drinking water, while 11.16% are completely dissatisfied. In Birsuat, 91.47% of respondents are rather satisfied, and 8.53% are completely satisfied with the quality of drinking water. In the Pavlodar region, 48.39% of respondents boil their water, 30.63% do not use any purification methods, 8.04% filter their water, 2.8% use cheesecloth, and the rest use other methods. In Birsuat, boiling is the only method used for water purification.

The findings of this study provide significant insights into the sanitation and water quality issues faced by rural areas in Pavlodar and Akmola regions. In Pavlodar villages, 73% of respondents have outdoor toilets, 19.78% have indoor toilets without access to a central sewerage system, and 7.22% have indoor toilets with access to the central sewerage system. In Birsuat, all toilets are located outdoors. In Pavlodar, 25.06% of toilets are located more than 50 m from the water source, 36.22% are 31–50 m away, 25% are 11–30 m away, and 11.23% are located inside the house. This spacing is crucial in mitigating contamination risks, as highlighted by Johnson et al. (2017) in their study on water safety in rural communities [27]. In the village of Birsuat, Akmola region, respondents indicate that the frequency of use of wastewater collectors ranges from two to seven times a year. This distribution aligns with previous studies highlighting the challenges in rural sanitation infrastructure [28].

According to our results, more than half of the respondents indicate paper, 28.54% other materials and 0.49% plastic as waste in toilets. The construction materials for toilets are predominantly wood (76.35%) with minimal use of brick, metal, or flat slate, which underscores the economic constraints and resource availability in these regions [29]. The prevalent toilet utilization method involves backfilling cesspools (76.22%), with fewer respondents using mechanical or chemical cleaning methods. This practice raises significant public health concerns due to the potential for groundwater contamination [30].

In Pavlodar villages, 76.92% of respondents believe that state representatives are responsible for both the public pump and the central water supply system, while 22.59% believe private companies are responsible. Additionally, 82% believe that the state is responsible for the safety of drinking water, 10.36% believe private companies are responsible, and 7.23% believe it is the responsibility of household owners. Almost all respondents (99%) indicate that household owners are responsible for maintaining toilets and disposing of wastewater.

The source of drinking water is positively associated with the use of water treatment products (correlation coefficient: 0.48), type of toilet used (0.34), and complaints about odor (0.39). Satisfaction with drinking water is correlated with hard water (0.43), salty water (0.64), bad taste (0.23), and precipitation (0.51). Responsibility for public pumps is correlated with responsibility for the central water supply system (0.59), and responsibility for central water supply correlates with responsibility for wastewater management (0.41) and complaints about bad taste (0.34).

The Water Quality Index is associated with salinity (0.64) and surface hardness (0.57). The relationship between the Water Quality Index and mineralization and general hardness highlights the critical parameters influencing water quality perceptions [31]. Mineralization of drinking water strongly correlates with total hardness (0.79). Complaints about sediments are correlated with complaints about salty water (0.48), foul odor (0.43), cloudy water

(0.4), and hard water (0.3). Complaints about salty water are correlated with complaints about unpleasant odor (0.57) and water hardness (0.43). Complaints about unpleasant odor are significantly correlated with complaints about unpleasant taste (0.43). Furthermore, the strong correlations between complaints about sediments, bad taste, hard water, and salty water suggest a compounded impact of multiple water quality issues on user experience [32].

There are many studies in the literature on the perceived quality of drinking groundwater, groundwater, and surface water separately and chemically different pollutants separately. For instance, the literature contains data on perceived water quality in the context of hazardous water contamination, such as that of arsenic. A cross-sectional study examined arsenic water contamination in locations with varying water quality problems and the psychosocial status of respondents. The study showed a strong positive correlation with arsenic-based psychosocial distress [33].

A study assessed the self-perception of quality of life in the Anil Canal area and the adjacent area of the Anil district center in Rio de Janeiro and identified factors associated with the self-esteem of the population. A cross-sectional observational analytical study of socio-demographic characteristics, general health, and sanitation was carried out. The self-perception of the need to improve the quality of life in the Anil Channel community and the Anil Central District zone was influenced by several social and economic factors, as well as living practices and conditions. In terms of the need to improve environmental quality of life, both areas are highly modifiable (e.g., ascariasis/roundworms; having a water tank in the house; not drinking bottled water; not having sidewalks outside). Sociodemographic and environmental factors, in addition to health status, play a critical role in influencing people's perceptions of the need to improve physical and environmental well-being [34].

Regarding the findings of this study, the perceived household water quality may influence bottled water consumption decisions in Greensboro, North Carolina neighborhoods across different income levels. Household surveys were used to examine residents' consumption of bottled and tap water and their stated reasons for drinking bottled water. The results of this study showed that intra-city differences in household water quality perceptions are a major environmental justice issue as safety concerns force low-income residents to spend their limited income on bottled water [35]. Poor sanitation, insufficient safe drinking water, and poor hygiene are the main causes of waterborne diseases. A cross-sectional study was conducted to explore the knowledge, behavior, and factors associated with sanitation and hygiene of residents living along canal banks in Ho Chi Minh City. Canal water systems in Ho Chi Minh City exceeded the permissible thresholds of Vietnam standards for discharges of total coliforms and E. coli. The reason for water pollution in canals is low public awareness. Incorrect knowledge and behavior of the local population regarding sanitation and environmental protection of the canal has led to increased water pollution in the canal [36].

According to the literature, off-grid water supply systems are still widely used in Indonesia, such as in Metro City, Lampung, where only 5.05% of households are served with piped drinking water. Metro City is known to rank fourth in Indonesia as an area with clean water quality problems. The method used was longitudinal monitoring of drinking water sources in households with monthly surveys. The monitoring results show that after 6 months of research, it was determined that non-self-provisioning systems are more secure than self-provisioning systems with a percentage of 98% and 95%. The highest safety source of drinking water was refilled water and bottled water (100%), which provided the most consistent level of safety [37]. An early study aimed to examine the knowledge, beliefs, and behaviors among historic well owners in two communities in southeastern Ontario to limit the adoption of protective measures. Participants were more concerned about events and changes from the outside than events and interruptions in the environment. This study provides insight into the key social-cognitive factors influencing behavior, as well as their characteristics and the characteristics of the consumption context of modern well owners [38].

The Nubui River is the main source of water for drinking purposes and other household activities. The river is contaminated with chemicals, heavy metals, and has obvious aesthetic water quality problems and health implications. The results of a study examining it showed a pattern of Hg < Pb < Cd < Zn < Fe and high levels of cadmium compared to World Health Organization drinking water guideline values [39]. Groundwater pollution is a serious environmental problem and can persist in a variety of environmental conditions. The study described the seasonal influence on pollution characteristics in combination with the degree of risk to human health in the groundwater of the city of Pakistan Lahore. Drinking Water Quality Indices (DWQIs) and Heavy Metal Pollution Indices (HMEsI) during the summer and winter seasons showed pollution patterns ranging from mild to moderate. The Pollution Load Index (PLI) and Potential Environmental Risk Index (PERI) indicated average levels of pollution with low risks. Using Monte Carlo simulations, it was found that the carcinogenic risks associated with As, Cr, Cd, and Ni exceeded safer limits. The winter season was perceived to be more sensitive due to a significant increase in the release of pollutants into groundwater and posing a serious threat to humans [40].

Research was conducted on access to safe drinking water and its determinants among households in East Africa. Approximately three-quarters of East Africa's population has access to improved drinking water, although water quality in the region is still considered poor [41]. Freshwater salinity syndrome (FSS), a concomitant increase in salinity, alkalinity, and concentrations of major cations and trace elements at the watershed scale were examined in relation to the potential influence of land use practices and wastewater treatment plant (WWTP) on the export of major ions and trace elements from a mixed-use watershed in south-eastern Pennsylvania. The positive relationship between the percentage of impervious surface cover, which ranged from 1.26% to 21.9% for the 13 sampled sites, and the concentrations of Ca^{2+}, Mg^{2+}, Na^{+}, and Cl^{-} was consistent with reverse cation exchange caused by road salt and weathering of the built environment. Chloride-to-sulfate mass ratios (CSMRs) indicated serious corrosive potential. Observed exceedances of drinking water criteria for Na^{+} and Cl^{-} occurred during the winter months [42].

Ground water is the most reliable source of water for rural areas and small communities without access to national water supplies. A study was conducted to assess the quality and hydro-chemical control of such wells in the Ashanti, Upper East, and Central regions of Ghana. Analysis of ground water in the Ashanti region showed that its quality is negatively affected by iron, manganese, and arsenic. Water Quality Index was used to evaluate the suitability of ground water for domestic purposes, and based on this index, 80% of the water samples were classified as having excellent or good quality and about 7% were classified as unsuitable for domestic purposes across all regions [43].

Ground water from various aquifers in the Zhanjiang area suffers from varying degrees of nitrogen pollution, which poses a serious threat to the health of urban and rural residents as well as the surrounding aquatic ecological environment. The results show that the hydrochemistry of ground water in different aquifers is complex and diverse, which is mainly influenced by rock weathering and precipitation, and the cation exchange is strong. High NO_3^- concentration reduces microbial community richness (VRPFW). Ground water contains large numbers of bacteria associated with the nitrogen (N) cycle, and nitrification dominates nitrogen conversion. Overall, NO_3^-/Cl^- data indicate that manure and wastewater (M&S) and soil organic nitrogen (SON) are the major sources of NO_3^- [44].

A study analyzing the functionality and sustainability of rural wells in Nigeria showed that while 49.8% of communities do not have improved water sources, 25.5% of communities rely on functioning wells, and 24.5% face problems [45]. A study of the quality of geospatial data for public drinking water distribution zones across all territorial authorities of Aotearoa New Zealand identified several differences in the quality of geospatial information that relate to population, area-level deprivation, ethnicity and, most notably, city classification/sat down [46]. In the US, drinking water violations are highest in low-income rural areas overall, and especially in Central Appalachia. An assessment was conducted of

public and private drinking water sources and associated risk factors for exposure to waterborne pathogens among people living in rural Appalachian Virginia. The results showed that tap water in the region was generally safe, and that people in low-income households without public water or sanitation were more susceptible to exposure to waterborne pathogens [47].

Based on the data from the United States, exposures—air pollution, drinking water contamination, and temperature extremes—and responses to these exposures differ in urban and rural settings. Although previous research has addressed some aspects of these issues, significant gaps in knowledge remain, largely due to historical shortcomings in monitoring and reporting, particularly in rural areas. It was found that the urban–rural gap in fine particulate matter (PM2.5) has converged over the past two decades, and the remaining gap is small compared to the overall decline. Moreover, residents of urban counties are, on average, less vulnerable to the mortality effects of PM2.5 exposure [48].

In many countries, the provision of drinking water in rural areas is the responsibility of the users themselves, but in practice the condition of the components of the implied infrastructure managed by RWS varies considerably. Using the example of Chile, the relationship between the state of infrastructure, performance, and organizational characteristics was explored. In addition, comparing the RWS attributes of these three clusters allowed us to characterize them in terms of structural, organizational, governance, and environmental variables [49].

Strengthening the methods and frequency of water quality monitoring and increasing public awareness of the importance of drinking water standards can help bridge the gap between perceived and actual water quality [50]. This study evaluated the water quality in ten rural villages, revealing significant variances in water parameter values, particularly concerning MPC exceedances. The predominance of hardness and mineralization across most villages indicates a widespread issue likely attributable to natural geological factors and insufficient local water treatment facilities [51]. In Gosplemstantcyia, the presence of multiple parameters such as natrium, kalium, and iron above the MPC highlights a critical concern for public health and the need for urgent intervention. The high iron levels and potential pollution sources, such as the nearby Aksu ferroalloy plant, suggests an anthropogenic influence likely exacerbated by inadequate waste management practices common in rural settings [52,53]. The elevated levels of nitrates in Zhertumsyk are associated with agricultural runoff mirror findings from similar studies in agricultural regions where fertilizer use is prevalent [54]. This underscores the ongoing challenge of managing agricultural pollutants, which requires integrated approaches involving both water treatment enhancements and agricultural best practices [55]. The situation in Chernoyarka, Shakat, and Zhanatan, where parameters like manganese were found above the MPC, could be indicative of both industrial influences and natural mineral deposits. Manganese contamination is particularly concerning due to its neurotoxic effects, necessitating immediate attention to water treatment processes and potential source identification [56]. The specific case of Shoptykol, where elevated levels of natrium and kalium are attributed to the dissolution of indigenous rocks, highlights the geogenic origin of some contaminants. This points to the natural variability of water quality and the critical need for context-specific interventions [57].

The chemical analysis of water samples revealed several concerning exceedances of Maximum Permissible Concentrations (MPCs) for substances such as iron, manganese, sodium, potassium, and nitrates in various villages. These findings correlate with the complaints of respondents about bad taste, hard water, and sediments, indicating a direct impact of water quality on user satisfaction [58,59].

In conclusion, the study underscores the urgent need for improved sanitation infrastructure and water quality management in rural areas. The findings call for targeted interventions to address the identified issues, ensuring safe and satisfactory water and sanitation facilities for rural communities. Future research should focus on developing sustainable solutions that are economically viable and culturally acceptable for these regions.

Given the diverse sources of contamination, ranging from natural geological conditions to anthropogenic activities, a multifaceted approach is essential. This includes improving local water treatment infrastructure, enhancing agricultural practices to minimize runoff, and implementing stringent industrial waste management protocols. Public awareness campaigns about the importance of water conservation and pollution prevention can further support these efforts.

5. Conclusions

Our study's analysis identified several key findings regarding the chemical composition of drinking water in the Pavlodar and Akmola regions. In the Pavlodar region, we observed that certain cations (such as iron in Naberezhnoye, Birlik, Zhertumsyk, and Koryakovka, and manganese in Chernoyarka and Zhanatan) and anions (notably nitrates) exceed the Maximum Permissible Concentration (MPC). These variations in chemical composition are interconnected with the type of water supply systems in each village and the water quality perceived by respondents. Different types of water supply systems are linked with the water quality perceived by respondents. For example, the type of toilet facilities among respondents is associated with the safe location and responsibility for water safety, which correlates with complaints about the bad taste of water. The type of toilet disposal also correlates with complaints about unpleasant odor and taste, hardness, and salinity of water. Responsibility for public pumps correlates with responsibility for the central water supply system and the type of wastewater disposal. The central water supply system's responsibility is linked to the type of wastewater disposal and complaints about unpleasant taste.

According to respondents, responsibility for water safety correlates with complaints about hard water, while responsibility for wastewater disposal correlates with the total microbial count of drinking water and complaints about salty water. The drinking Water Wuality Index is closely related to water mineralization and overall hardness. The total microbial count of drinking water has a significant relationship with respondents' complaints about unpleasant taste, smell, and salinity. The mineralization of drinking water is closely related to its overall hardness. Respondents' complaints about sediment in water are interrelated with complaints about hardness, salinity, turbidity, and unpleasant odor. Complaints about salty water are closely related to complaints about unpleasant odor and hard water, and complaints about unpleasant odor are related to complaints about unpleasant taste.

This study provided a comprehensive assessment of drinking water quality in rural areas of the Pavlodar and Akmola regions, highlighting significant issues related to water hardness, mineralization, and specific contaminants such as iron, nitrates, and manganese. The findings underscore the need for targeted interventions to address both natural and anthropogenic sources of water contamination. Ensuring safe drinking water in these regions requires a coordinated effort involving local authorities, industrial stakeholders, and the rural communities themselves. Regular monitoring, public education, and improved infrastructure are pivotal in safeguarding the health and well-being of the rural population.

This investigation also highlighted significant variances in water quality and sanitation infrastructure in the rural areas of the Pavlodar and Akmola regions. The findings indicate that a majority of residents rely on outdoor toilets and private water sources, with varying levels of satisfaction with drinking water quality. Key issues include water hardness, salinity, and contamination from nearby industrial activities. There is a strong need for improved sanitation infrastructure, better water treatment facilities, and increased public awareness of water quality standards. Future research should focus on sustainable, economically viable, and culturally acceptable solutions to address these challenges. To improve the quality of water related to the sanitary condition of villages, namely the location of toilets and cesspools, it is necessary to clearly regulate the location of toilets and their disposal points from the water supply source. It is also important for residents to be aware of the standards for safe disposal and maintaining toilets in sanitary conditions in villages.

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Determination of the Risk on Human Health of Heavy Metals Contained by Ship Source Bilge and Wastewater Discharged to the Sea on the Mediterranean by Monte Carlo Simulation

Ömer Harun Özkaynak *, Gönül Tuğrul İçemer and Hasan Merdun

Environmental Engineering, Akdeniz University, Antalya 07000, Turkey; gicemer@akdeniz.edu.tr (G.T.İ.); merdun@akdeniz.edu.tr (H.M.)

* Correspondence: 20165108003@ogr.akdeniz.edu.tr

Abstract: Discharge of bilge and wastewater from ships into the sea poses a risk to human health due to the heavy metals. In this study, shipborne bilgewater and wastewater carcinogenic and non-carcinogenic human health risks determine by using the measured and literature values of heavy metals copper, iron, vanadium, chromium, manganese, cobalt, nickel, zinc, arsenic, cadmium, and mercury in the shipborne bilgewater and wastewater. The heavy metal contents of seawater were selected from 11 points determined in Antalya Bay, wastewater, and bilge samples taken from two ships. The human health risk was determined using the Monte Carlo Simulation (MCS) method using these measured values and the heavy metal concentrations in the Mediterranean Sea in the literature. The risk of carcinogenicity of heavy metals from wastewater by dermal route, ingestion, and from bilge water by dermal way and ingestion were evaluated. The wastewater is dermal Ni > As > Cr, the wastewater is Ni > Cr > As by ingestion, the dermal Ni > As > Cr in the bilge, and the risk of ingestion is Ni > Cr > As. It has been determined that the non-carcinogenic Cr, Co, Hg, and As values in the wastewater and bilge water are above the acceptable 1 and therefore expose a risk to human health. The human health carcinogenic risk caused by heavy metals generating from the bilge and wastewater is much higher than the standard values determined by the WHO. For the first time in this study, it was determined that bilge water exposes a high risk for both swimmers and ship personnel in the health risk assessment of shipborne wastewater and bilge water.

Keywords: heath risk; environment pollution; heavy metals; marine pollution; coast pollution; Monte Carlo Simulation

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1. Introduction

It is known that heavy metals have serious adverse effects on human health. As a result of the discharge of bilge and wastewater generating from ships in the seas, the removal of the heavy metal contained in these wastes by the marine species, or the exposure of people to these heavy metals because of their activities in the sea poses a risk to human health. Bilgewater may contain fuel, hydraulic oils, lubricating oils, volatile organic compounds, metals, detergents, degreasers, other chemicals derived from activities on a ship [1].

Mediterranean coasts are among the marine areas where the risk of leakage of oil and petroleum-derived wastes is high due to approximately 25% of the world's ship traffic [2]. According to the Barcelona Convention, 22 Mediterranean countries have also attracted the attention of the world tourism industry with their cultural diversity and natural beauties. For this reason, it is estimated that the population in the coastal and urban areas of the Mediterranean region will increase rapidly and reach 572 million by 2030 [3].

Considering the terrestrial, atmospheric and natural leakage inputs to the Mediterranean, no consensus could be reached on the actual amount of oil. However, the annual volumes (metric ton) of these inputs are reported to be 32,000 [4], between 400,000 and

1,000,000 [5], and between 15,000 [6] and 63,500 t [7] Due to these high inputs, heavy metals from petroleum hydrocarbons have serious adverse effects on human and ecosystem health [8,9]. As a result of the discharge of bilge and wastewater generating from ships in the sea, marine species [10] or human exposure to heavy metals contained in these wastes [11,12] activities in the sea expose a risk to human health.Heavy metal content may be high in these chemicals with the contribution of ship activities. With these metals, some parts of the Mediterranean coast are polluted by human activities in the sea and on the coast [13–15]. Heavy metals such as lead, mercury, cadmium, zinc and copper are found in coastal deposits in the Northern Mediterranean. This is explained by the fact that it is associated with industrial and domestic waste discharges and activities in the Ports [16].

Marine animals can take heavy metals in seawater, transferring to lower levels in the food chain with biomagnification through direct mouth or skin contact [17]. Even in small amounts, heavy metals can harm marine species, so their access to seawater should be controlled. Heavy metals are also called trace or trace elements. Generally, its commonly found in seawater are Sb, Ag, As, Be, Cd, Cr, Pb, Mn, Hg, Ni, Se, T, U, V, Zn, Al, and Cu. The severe increase of heavy metal accumulation in the seas due to human activities is an important issue due to environmental pollution, risks to human health, sea fauna and flora [18,19].

Heavy metals cause severe sea pollution [20] and can accumulate in large quantities on the coasts. It has been determined that people on the beaches can be easily affected by heavy metals by body contact with beach sand and swallowing seawater [21,22]. In the study conducted by [23], in the Antalya Kemer region, it was determined that Ca, Cr, Fe, Ti, and Pb were abnormally concentrated in the samples taken from 47 points and Cr, Pb, and Cu showed high-risk levels as contaminants in some samples. In addition, it was stated that the formation of high Cr concentration was caused by biological activities, while Pb and Cu were formed due to human activities.

The amounts of heavy metals (Cd, Fe, Cu, Pb, Zn, Co, Cr, Al, Mn, and Ni) in seawater in the Iskenderun Bay were investigated by Turkmen (2011) [24]. Author found that the concentrations of Al, Cr, Fe, Cu, and Se elements were found above the limit values. Similary in the same region, Göycıncık et al. (2018) [25] measured the concentration of 8 heavy metals (B, Al, Cr, Fe, Ni, Cu, As, Se) in seawater samples. According to the results obtained from their studies, it was determined that the concentrations of B, Al, Cr, Fe, Cu, and Se elements were above the limit values, and Ni and As elements were below the limit values. According to Yalcin et al. (2016) [26], in a study conducted in Mersin and Alanya, sediments at 44 points were compared with literature data based on the examination of the samples; It has been determined that the average heavy metal concentrations in Turkey are large enough to be considered toxic and above acceptable value.Wastewater from ships contains high concentrations of pollutants such as heavy metals, nutrients and suspended solids [27]. It has been reported that wastewater from many ships contains heavy metals and their discharge into the sea damages the marine ecosystem [28]. Heavy metals [29] and heavy metal concentrations [30] were determined in studies on the content of bilge water. In the western Mediterranean, [31] compared the amounts of heavy metals in summer and winter seasons, and it was determined that the values measured in the winter months were higher. In the Baltic Sea study conducted by Tiselius and Magnusson (2017) [32], the bilge water's oil and heavy metal content was estimated to be 4 to 8 times lower.

Environmental risk is the possibility that the activity carried out will adversely affect human health or the environment directly or indirectly; the risk assessment for estimating the magnitude of this risk. In 13 different reports containing data on pollutant concentrations in gray waters formed on ships, it is stated that there are 44 (28 organic, 16 metal) different pollutants in gray waters [33]. As a result of their studies, it has been determined that zinc and copper metals pose the highest environmental risk in grey wastewater.

Regarding the evaluation of ecological risk with Monte Carlo analysis, Dang et al. [34] determined the highest contamination risk in water with a value of Cd, 2.06 ± 0.78 mg L^{-1}, whereas Kuang et al. [35] determined the risk of heavy metals as, respectively, As > Cd > Cr

in sediment and marine organisms. Soleimani et al. [36] estimated the risk of heavy metals Cr, Pb, and Cd in drinking water with 10,000 iterations using the same method.

Arikibe and Prasad [37] was found heavy metal concentrations Ni 0.23–0.80 mg L^{-1}, Zn 0.08–1.45 mg L^{-1}, Cd 0.15–0.25 mg at the sampling site in Suva Fiji Pb 0.88–1.77 mg L^{-1} and Cu 0.88–10.29 mg L^{-1} and no risk analysis was performed. According to the WHO guideline, only the measured values were evaluated. It was determined that the Cd and Pb values were above the accepted values [38].

Heavy metal concentrations were calculated using MCS to determine risk calculations from 36 samples taken from Lake Nancy [39]. Risk analysis was performed using the SPSS program and measuring seven heavy metals (Cr, Cu, Ni, Zn, As, Pb and Cd). It was calculated with the potential ecological risk index (RI) formula. Cu and Cd values were above the accepted values and posed a risk.

The spatial distribution, potential sources, and ecological risks of 8 heavy metals (Zn, Cu, Cr, Ni, As, Cd, Hg, and Pb) in Meishan Bay, the Zhejiang coast of China with a high pollution load, were investigated. It is accepted that Zn is mainly caused by ship transportation; pesticides and Hg from sewage wastewater are considered the primary sources. In contrast with the MCS, the Geo-accumulation index was used, and it was determined that Cu, Zn, Cr, Pb, and As pollution was limited, while Cd and Hg caused light to moderate pollution [40].

The Mining factory found that the potential health risk (through ingestion and skin contact) calculated for lifetime exposure is cumulative for workers, tourists, and residents (including children and adults) depending on the magnitude of heavy metal pollution in the surrounding Qixia landscape site [21]. Carcinogenic and non-carcinogenic risks were determined using the MCS method. The method selects the values of the parameters from the distributions fitted to the input data and, as a result, calculates both the point value and the exposure and risk distribution [41–43].

As seen in the reviewed literature, no study has been found on the human health risk of wastewater and bilge water generating from ships. This study determines the carcinogenic and non-carcinogenic risk to human health caused by the heavy metals in the shipborne wastewater and bilge water mixing with the seawater in the short term through the skin and ingestion for the first time.

There is no study evaluating the health risk from the bilge and wastewater of ships in Antalya Bay. For this reason, the primary objective is to calculate the health risks of heavy metals, the amount of which increases in seawater due to possible illegal discharges of bilge and wastewater and other inputs. In this context, calculations were made using the current measurement values and the literature values in the Mediterranean.

2. Material and Methods

2.1. Study Area

Antalya's coastal length extends from Eşen Stream in the west to Kaledron (Kaldıran) Stream in the east at 640 km. This coast length is 40% of the Mediterranean Region's coastal line. This region is the center of tourism with a population of close to 3 million and natural beauties.

There is a "fisherman port" and a "harbor" that houses a "fisherman port" and a "harbor" house cargo ships, cruise ships, and a marina among the coastal structures within the area. The Antalya port is among the top 10 ports where the most cargo is handled [44]. When we examine the number of ships arriving at Antalya port in the last three years, 1109 ships in 2019, 728 in 2020, and 778 in 2021.

There is also a filling facility on the shore transported by oil pipelines. The world-famous Konyaaltı beach (6.5 km.) is one of the recreational areas for public use in the coastal region and the beach welcomes about 5000 people daily in high season [45].

2.2. Sample Collection and Preparation

In this case, 44 seawater samples were taken from 11 selected points in the Antalya Bay in February, April, July, and November, covering all four seasons. The sampled sea area is given in Figure 1. Bilgewater and wastewater samples were taken from a daily excursion boat larger than 12 m and a commercial vessel larger than 100 m in length. The samples taken for heavy metal analysis were stored in the refrigerator at +4 °C by adding nitric acid. Heavy metal analyzes were performed with an Energy dispersed NEX CG X-ray fluorescence spectrometer (XRF) with a 50W artificial X-ray tube from Rigaku. Approximately 50 mL of sample was put into the device for heavy metal analysis, and measurements were made in mg L^{-1}.

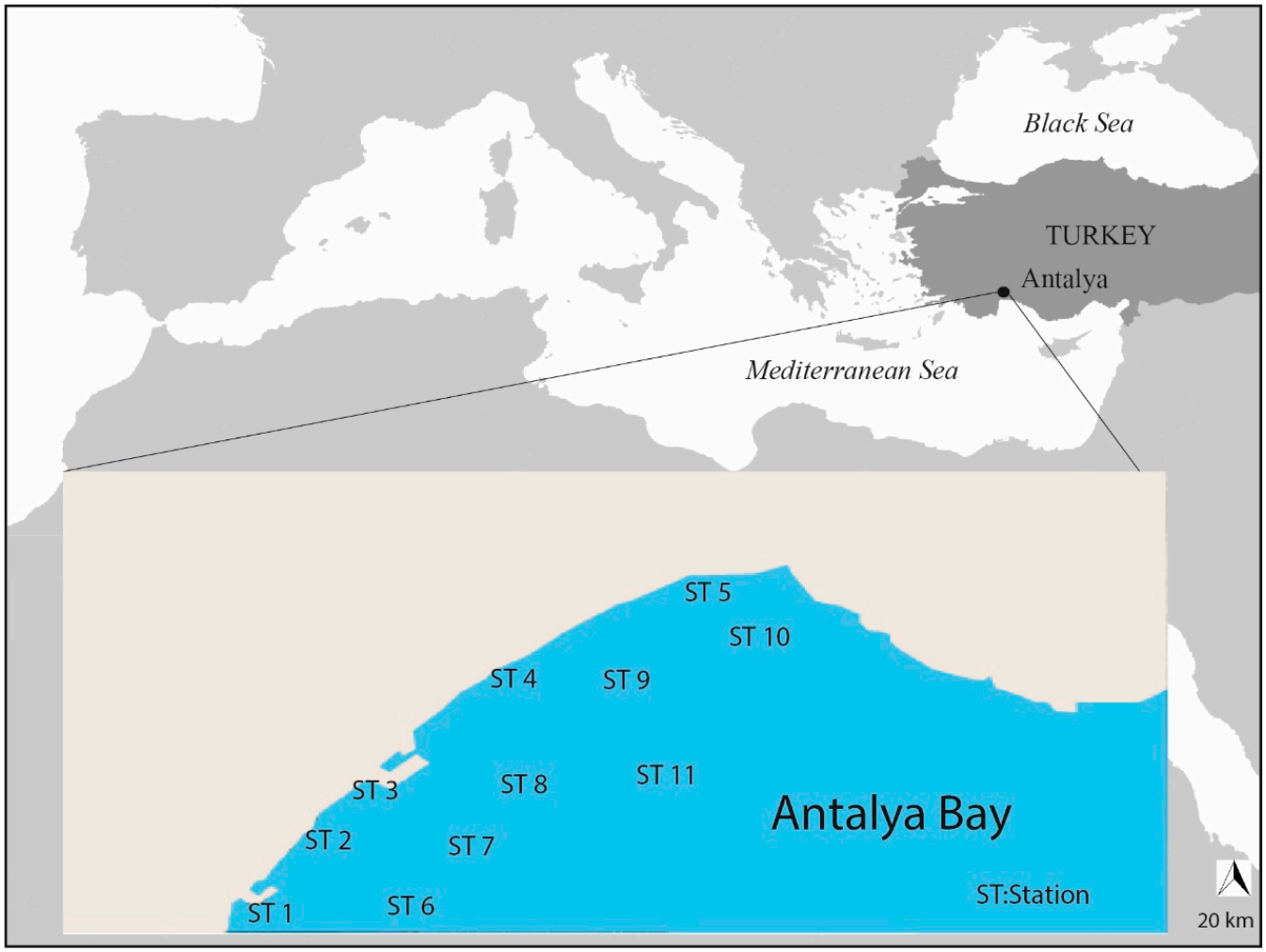


Figure 1. Study area and sampling points in the study area.

The accuracy and precision of the heavy metal analysis results were checked with standard reference material analysis [46]. Measurement limits were determined using the reference standard value for each heavy metal.

Quality assurance and control measures were adopted. The accuracy of the measurements was checked using the standard solution and heavy metal reference values. The measurements were statistically controlled for each heavy metal measurement as maximum, minimum, and standard deviation (S.D.).

2.3. Determination of Human Health Risk Caused by Bilge and Wastewater with MCS

Ideally, probability distributions of variables should be based on underlying physical processes or mechanisms that are considered key in causing the observed variability. For

example, if the exposure variable results from many other random variables, choose a lognormal distribution for testing [47]. Since risk was calculated as a distribution using MCS, the risk was calculated using the lognormal distribution in this study.

MCS is a common method used to evaluate uncertainty through probability distribution functions. In this study, the heavy metals Cu, Fe, S, V, Cr, Mn, Fe, Co, Ni, Zn, As, Cd, Hg, and Pb in the contents of the bilges and wastewaters originating from the ships were measured with MCS using the values in the literature and the concentration values in the Mediterranean to determine human health risk.

Since it is known that people will be exposed to heavy metals in the sea by the risk equation provided in RAGS (Risk Assessment Guidance for Superfund), Volume 3 [48], the formula used to calculate this risk is [49–51]; and the carcinogenic risk was determined using the following formulas;

$$Risk\ (\text{ingestion}) = CSF\frac{C \times IR \times EF \times ED}{BW \times AT} \quad (1)$$

$$Risk\ (dermal) = CSF\frac{C \times SA \times Kp \times ET \times EF \times ED \times 10}{BW \times AT} \quad (2)$$

where C is the concentration of the chemical in an exposure environment mg L^{-1}, SA is the area of the exposed surface (m^2), EF is the exposure frequency (days $year^{-1}$), ED is the exposure time (years), BW is the body weight (kg), AT is the meantime. (Admitted as 70 years for carcinogen and 30 years for others), ET exposure time (h day^{-1}), Kp, skin permeation coefficient through underwater exposure (cm h^{-1}), IR, uptake rate (L day^{-1}), and CSF expresses the cancer slope factor (linear low dose cancer potential factor) (mg $kg^{-1}day^{-1})^{-1}$ for the chemical.

In this study, CSF, AT, ED, and Kp values were entered into MCS as constant. Five elements (Cr, Cd, As, Ni, and Co) are classified as possible carcinogens by the International Agency for Research on Cancer [52]. The CSF values used in calculating heavy metals with MCS are given in Table A1. The non-carcinogenic risk of heavy metals was determined using the following formulas;

$$Risk\ (\text{ingestion}) = \frac{C \times IR \times EF \times ED}{BW \times AT}/RfD \quad (3)$$

$$Risk\ (dermal) = \frac{C \times SA \times Kp \times ET \times EF \times ED \times 10}{BW \times AT}/RfD \quad (4)$$

where C is the concentration of the chemical in an exposure environment (mg L^{-1}), IR is the uptake rate (L day^{-1}), EF exposure frequency (days $year^{-1}$), ED exposure time (years), BW is body weight. (kg), AT meantime (accepted as 70 years for carcinogens and 30 years for others), SA area of exposed surface (m^2), Kp, coefficient of permeability of skin through underwater exposure (cm h^{-1}), ET exposure time (h day^{-1}), and RfD (mg $kg^{-1}day^{-1})^{-1}$ refer to the reference dose.

The lognormal distribution was chosen as the exposure variable for heavy metal concentrations and is also the result of many other random variables [47]. In the study conducted by Chen et. Al [53], it was determined that the distribution of V was close to the normal distribution, while other potentially harmful elements showed non-normal distribution characteristics. The constant values obtained from the literature and used in the risk formula in this study are given in Table A2.

In this study, some values were taken from the literature to calculate risk assessment by skin and ingestion. Kp values (1×10^{-3} for Cd, Cr, As, Fe, Mn, Co, V, and Hg; 1×10^{-4} for Pb; 6×10^{-4} for Zn; 2×10^{-4} cm for Ni) are taken from the Exposure Factors Handbook [54]. CSF is the pollution factor of an element calculated using values measured in the past [55]. CSF values expressed as IR, and uptake rate (L day^{-1}) were taken from Javed and Usmani [56] and Chen [53]. For the AT value in this formula, 70 years for carcinogenic substances were used as 30 years for non-carcinogenic substances [53]. Five of

the heavy metals (Cr, Cd, As, Ni, and Co) were classified as possible carcinogens by the International Agency for Research on Cancer [52]. Calculations were made by considering the same metals as carcinogens in this study. Similarly, Custodio et al. [53,57] made calculations with the acceptance of literature values in the studies of determining the risk to human health.

3. Results and Discussion

3.1. Measured Values

According to the heavy metal analysis results of seawater samples taken from 11 selected points in Antalya Bay in February, April, July, and November, covering four seasons, the average values of heavy metals were Fe 5.78 mg L^{-1}, Cu 2.67 mg L^{-1}, and Zn 3.97 mg L^{-1}. Among other heavy metals, Cr could be measured in winter at station 2 and in summer at station 11, while Hg was within the measurement limits at station 5 in winter and spring, at station 10, and at stations 3 and 4 in summer. The results of the studies on heavy metal concentrations of seawater in the Mediterranean and the comparison of the limit values of these metals in Turkey and the World Health Organization [38] are given in Table 1.

Table 1. Results of studies on heavy metal concentrations in seawater in the Mediterranean.

Metal	Türkmen [24] mg L^{-1}	Göycincik et al. [25] mg L^{-1}	Morley et al. [31] mg L^{-1}	Present Study mg L^{-1}	Standard Values (Surface Water Quality Management Regulation (SWQMR)) Annual Average [58] mg L^{-1}	WHO ** [38] mg L^{-1}
Cr	0.17	0.24	n/d	0.69	0.042	0.05
Cu	0.07	0.36	n/d	2.67	0.013	NGL
Ni	0.28	0.09	0.013	n/d	0.086	0.5
Pb	0.62	n/d	0.01	n/d	0.013	0.01
Zn	0.07	n/d	n/d	3.99	0.533	NGL ***
Fe	0.30	7.14	0.01	5.84	0.036	NGL
As	* n/d	0.05	n/d	n/d	0.01	0.01
V	n/d	n/d	n/d	n/d	0.016	NGL
Mn	0.11	n/d	n/d	n/d	0.1–0.5	NGL
Co	0.26	n/d	0.01	n/d	0.003	NGL
Cd	0.06	n/d	n/d	n/d	0.002	0.03
Hg	n/d	n/d	n/d	15.11	0.007	0.06

* n/d = Not Detected, ** Converted from μg/L to mg/L, *** NGL = no guideline limit.

Measurement results in the literature and samples in bilge water are given in Table 2. The measurement results in wastewater and in the literature are shown in Table 3.

When the Cu, V, and Zn values measured in the bilge water in this study are compared, it is seen in Table 2 that the importance of other researchers is much higher.

The values of Cu, Fe, and Zn measured in this study in wastewater were higher than those determined by Ytreberg [33], Onwuegbuchunam et al. [59], and Mearns et al. [60], as it is shown in Table 3. In addition, the measurement method used in this study could not determine S, V, Mn and Hg values in wastewater. Therefore, risk distributions were also calculated.

In this study, the averages of heavy metal values measured based on stations are given in Table A3. The values of Cu and Cr measured in this study in seawater were 2–3 times higher than those determined by Türkmen [24] and Göycıncık et al. [25]. The Zn values were 4 mg L^{-1}, much higher than the value (0.0709 mg L^{-1}) measured by Türkmen (2011).

Fe amount was measured as 5.84 mg L^{-1} in this study. Göycıncık et al. [25] (2018) determined the Fe value as lower than 7.142 mg L^{-1} measured in this study.In addition, the amount of Fe measured in this study was found to be 0.29 mg L^{-1} measured by Turkmen [24], and Morley et al. [31] were determined to be much higher than the 0.00088 mg L^{-1} measured. It was observed that the Hg value measured at four stations was 15.11 mg L^{-1} and could not be determined or remained below the measurement limits in the studies given in Table 1.

Table 2. Heavy metal values measured in the bilge water in this study and the literature.

Studies on Bilge Water	Tiselius and Magnusson [32] mg L^{-1}	Olorunfemi et al. [30] mg L^{-1}	EPA [61] mg L^{-1}	Present Study Passenger Boat mg L^{-1}	Present Study Merchant Ship mg L^{-1}
Cu	0.0254 ± 0.0131	0.5	0.2775–0.426	2.85	3.87
Fe	3.204 ± 0.132	n/d *	0.432–0.531	n/d	81.8
V	0.0378 ± 0.0234	n/d	n/d	n/d	1.51
Cr	0.0192 ± 0.00853	1.4	n/d	n/d	n/d
Mn	0.161 ± 0.0588	3.9	n/d	n/d	n/d
Co	0.0897 ± 0.0604	n/d	n/d	n/d	n/d
Ni	0.0754 ± 0.0192	0.3	0.09775–0.245	n/d	n/d
Zn	0.310 ± 0.066	11.6	0.514–1.33	4.18	13.6
As	0.00191 ± 0.00034	n/d	n/d	n/d	n/d
Cd	<0.0002	0.1	n/d	n/d	n/d
Hg	0.00279 ± 0.00114	n/d	0.03205–0.0798	n/d	n/d
Pb	<0.004	n/d	N/A	n/d	n/d

* n/d = Not Detected.

Table 3. Heavy metal values measured in the wastewater in this study and the literature.

Studies on Heavy Metal in Wastewater	Ytreberg et al. [33] mg L^{-1}	Onwuegbuchunam et al. [59] mg L^{-1}	Mearns et al. [60] mg L^{-1}	Present Study Passenger Boat mg L^{-1}	Present Study Merchant Ship mg L^{-1}
Cu	0.267	0.0012	0.0829	2.47	1.68
Fe	n/d *	0.00202	n/d	n/d	8.7
V	n/d	n/d	n/d	n/d	n/d
Cr	0.0073	n/d	0.00342	n/d	n/d
Mn	n/d	n/d	n/d	n/d	n/d
Co	n/d	n/d	n/d	n/d	n/d
Ni	0.025	n/d	n/d	n/d	n/d
Zn	0.517	0.00004	0.13	4.63	4.64
As	0.006	n/d	0.0092	n/d	n/d
Cd	0.00016	0.00025	n/d	n/d	n/d
Hg	0.00016	n/d	n/d	n/d	n/d
Pb	0.0256	n/d	0.00296	n/d	n/d

* n/d = Not Detected.

3.2. Determination of Human Health Risk Caused by Bilge and Wastewater with MCS

In this study, the heavy metal data of Cu, Fe, S, V, Cr, Mn, Fe, Co, Ni, Zn, As, Cd, Hg and Pb in seawater and ship-sourced bilge and wastewater to determine the health risk with MSC, measured in Antalya Bay concentrations and values measured in the literature.

The human health risk of each heavy metal was determined by using the values in the risk formula specified in the Materials and Methods section and the values were given in Tables A2–A4. In this study's highest and lowest risk values of carcinogenic and non-carcinogenic heavy metals calculated using MCS are shown in Table 4. The RfD values used in calculating the heavy metals analyzed and obtained from the literature data with MCS are given in Table A1.

Al, Ba, Cu, Fe, Sr, and Zn metals were determined as a result of the study on the integrated environmental assessment of the bioaccumulation of heavy metals in invertebrates and seaweeds from different marine coastal regions of Sardinia inthe Mediterranean [62]. It has been determined that this may affect human health, but the source of heavy metals has not been investigated.

In a study, the total exposure index and cumulative risk resulting from exposure to only trihalomethanes in drinking water were calculated using MCS [63].

When we examine the literature, it is seen that only heavy metal amounts in bilge and wastewater originating from ships are investigated (Tables 1–3). In this study, in

contrast with the literature, the human health risk of heavy metal amounts was determined using MCS.

Table 4. The highest and lowest risk values of carcinogenic and non-carcinogenic heavy metals were calculated using MCS.

Statistics	Wastewater Ingestion	Bilge Water Ingestion	Wastewater Ingestion	Bilge Water Ingestion
	Carcinogenic Risk		Non-Carcinogenic Risk	
Cr	0.3	0.38	1.69	2.85
Ni	0.59	0.81	n/c	n/c *
As	0.12	0.11	3.06	0.03
Co	n/c	n/c	2.56	1.7
Hg	n/c	n/c	n/d **	3.4

* n/c: not calculated, ** n/d = not detected.

3.3. Determination of Carcinogenic Risk Distribution

The human health carcinogenic risk values calculated by the MCS method originating from heavy metals in the bilge and wastewater contents are given in Table A4.Our results showed Table A4 that the highest carcinogenic risk to human health was Ni in the bilge water taken by swallowing with 8.06×10^{-1} and the lowest risk was determined the Cr in wastewater with 5.32×10^{-4} by ingestion. Considering that the limit value defined by WHO for Ni from these values is 0.5 mg L^{-1}, it is seen that the 0.81 mg L^{-1} value calculated by MCS using the values in the literature poses a significant risk for human health as a carcinogen. For Cr, the risk of ingestion of wastewater ingestion is 0.29 mg L^{-1}, and the risk of ingestion through the skin from the bilge water is 0.38 mg L^{-1}, which is above the limit value of 0.05 mg L^{-1} determined by WHO.

It was determined that all of the calculated risk values for Ni were above 0.5 mg L^{-1}, which is the limit value determined by the WHO. The limit value As determined by the WHO is 0.01 mg L^{-1}, the wastewater ingestion risk is 0.13 mg L^{-1}, and the risk of ingestion of bilge water is calculated as 0.11 mg L^{-1}. It is seen that these values are well above the limit value. The MSC risk distribution of the contamination of Ni in the bilge water by ingestion is given in Figure 2. MCS risk distribution graphs of other heavy metals are shown in Figure A1. The carcinogenic risk distributions of Cd and Co could not be calculated since they did not have CSF values.

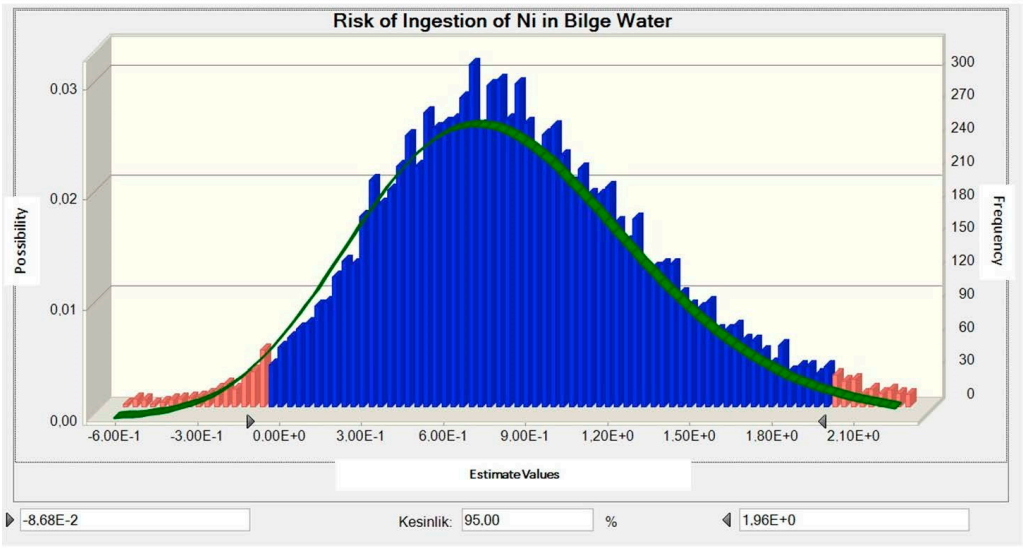


Figure 2. Contamination risk distribution by ingestion of Ni in the bilge water calculated by MCS.

In the study using MCS, non-carcinogenic oral (1.10×10^{-4}) and dermal (1.47×10^{-4}) and carcinogenic oral (1.88×10^{-6}) and dermal (1.41×10^{-6}) children exposed to arsenic in petroleum-derived oils on beaches, it was determined that the risk of carcinogen by the dermal route is higher in the risk assessment. The overall risk estimates are highest (2.88×10^{-5}) for the dermal exposure route [64].

The study determined the health risk that may occur only by swallowing drinking water. In addition, carcinogenic and non-carcinogenic risk has not been examined [65].

When the risk of dermal uptake of heavy metals from wastewater is evaluated, it is determined that the order is Ni > As > Cr, and the risk of ingestion from wastewater is Ni > Cr > As. The risk of dermal ingestion of heavy metals in the bilge is Ni > As > Cr, and the risk of ingestion is Ni > Cr > As.

3.4. Determination of Non-Carcinogenic Risk Distribution

Non-carcinogenic risk values for human health calculated by the MCS method originating from heavy metals in bilgewater, wastewater, and seawater are given in Table A5. This study found that the heavy metal, which constitutes the highest non-carcinogenic risk for human health, was 3.39 and Hg in the bilge water content, and the lowest risk was 5.12×10^{-5} and Zn in the wastewater content. It has been determined that there is a risk of transmission through the skin. If the calculated heavy metal non-carcinogenic risk is greater than 1, it indicates the probability of adverse health effects, and less than 1 shows no adverse health effects [54]. It was determined that the Cu, Fe, V, Mn, Ni, Cd, and Pb values were below one and did not have a negative effect on human health.

It has been determined that the human health risk caused by ingestion of Cr in the wastewater content is 1.69 mg L^{-1}, and the human health risk caused by ingestion in the bilge content is 2.85. Similarly, it has been determined that the human health risk caused by ingestion of Co in the wastewater content is 2.56, and the human health risk caused by ingestion in the bilge content is 1.7. In addition, it has been determined that the human health risk caused by ingestion of As in the wastewater content is 3.06 mg L^{-1}, and the human health risk caused by ingestion of Hg in the bilge content is 3.4, which is the highest risk. It has been determined that the order of the non-carcinogenic total risk values in the bilge and wastewater content is As > Cr > Co > Hg. Since the values are above the acceptable value of 1, it has been determined that it poses a human health risk.

3.5. Results Analysis

The study conducted in Meishan Bay in 2020 determined that the leading cause of Zn was shipborne, and Hg was caused by wastewater [40]. Similarly, in this study, as given in Table 1, the Zn value was measured as 3.99 mg L^{-1} and the Hg value as 15.11 mg L^{-1}. Therefore, it is considered that ship activities may cause heavy metal pollution in the Mediterranean. It has been determined that Zn in wastewater from ships poses a severe environmental risk. Similarly, this study measured 4.63 mg L^{-1} and 4.64 mg L^{-1} values in wastewater samples taken from ships [33].

Several studies evaluated that human activities cause heavy metal pollution in the seas [13,18,19]. However, these studies did not examine heavy metals at sea from which human activity originates.

In the study conducted the Northern Mediterranean, heavy metal pollution of Hg, Zn, Cd, and Cu was determined [16]. It was determined that this could be due to the ship activities in the ports. Similarly, in this study, as seen in Table 1, Hg, Zn, and Cu values were measured above the acceptable limits [38,58]. Therefore, it has been evaluated that the heavy metal pollution values obtained in this study may be caused by ships.

As stated above, this environmental risk caused by heavy metals can also pose a severe risk to human health. This study determined that there may be a health risk if people are exposed to heavy metals that may originate from ships in the Mediterranean. However, the effects of these wastes on heavy metals in sea water were not investigated in the studies given in Tables 2 and 3 about heavy metals in sea water and the bilge and wastewater

from ships. Therefore, the study is the first to examine the human health risk of bilge and wastewater discharged into sea water. To better understand the results of this study, more detailed studies should be carried out by taking these results as a reference.

4. Conclusions

Based on the European Parliament's Water Framework Directive (WFD) (Directive 2000/60/EC), the heavy metal concentrations that should be in seawater have been determined according to the "Surface waters management regulation" issued within the scope of the European Union harmonization in the formation of water policy in our country. According to this legislation, the heavy metal concentrations measured in seawater were evaluated, chromium was 16 times higher, zinc 7.5 times higher, and iron 162 times higher.

In the carcinogenic risk calculation, the dermal ingestion of heavy metals from wastewater is listed as Ni > As > Cr from the highest to the lowest, and the risk of ingestion from the wastewater as Ni > Cr > As from the highest to the lowest. The dermal ingestion of heavy metals in the bilge is determined as Ni > As > Cr from highest to lowest and Ni > Cr > As for ingestion risk.

The non-carcinogenic risk assessment calculated that the Cu, Fe, V, Mn, Ni, Cd, and Pb values were below 1 and did not harm human health. However, it can be predicted that it can cause other diseases. Non-carcinogenic risk calculations of the specified heavy metals in the bilge and wastewater were totally evaluated by skin and ingestion.It has been determined that the order of the non-carcinogenic total risk values in the bilge and wastewater content is As > Cr > Co > Hg. Since the values are above the acceptable value of 1, it has been determined that it poses a human health risk.

It has been calculated that the human health risk of Cr, Ni and As is much higher than the values determined by WHO and that the bilge and wastewater have carcinogenic risks for human health. It is thought that this risk will be pretty high for the personnel working as technical personnel on the ship and the swimmers due to illegal discharges. This study recommended taking and controlling protective measures to reduce the risk of carcinogens in dermal and inhalation.

Since the human health risk of heavy metals in the contents of wastewater and bilge waste from ships was evaluated with the MCS method for the first time in the study, the results of the current research should be assessed as a basis. When the results obtained from this study were evaluated, it was seen that the bilge and wastewater wastes from ships on our seas and coasts pose a serious human health risk. It is considered that this risk can only be avoided by taking adequate measures and carrying out strict controls. It has emerged that there is a need for research, including measures such as prevention of wastewater and bilge water leakage discharges and re-examination of waste reception systems in ports and marinas.

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Appendix A

Table A1. The CSF values used in calculating heavy metals with MCS.

Contaminant of Potential Concern	Oral CSF (Chen, 2019)	Dermal CSF (Chen, 2019)	Oral CSF (Soleimani vd. 2020)	Oral RfD (Chen, 2019)	Dermal RfD (Chen, 2019)
	$(mgkg^{-1}day^{-1})^{-1}$	$(mgkg^{-1}day^{-1})^{-1}$	$(mgkg^{-1}day^{-1})^{-1}$	$(mgkg^{-1}day^{-1})^{-1}$	$(mgkg^{-1}day^{-1})^{-1}$
Pb	n/d	n/d	0.002	1.40×10^{-3}	5.25×10^{-4}
Cr	5.01×10^{-1}	2.00×10^{1}	n/d	3.00×10^{-3}	3.00×10^{-3}
Cd	n/d	n/d	0.005	5.00×10^{-4}	1.00×10^{-5}
Mn	n/d	n/d	n/d	1.40×10^{-1}	2.33×10^{-2}
Co	n/d	n/d	n/d	3.00×10^{-4}	6.00×10^{-5}
Ni	1.70	4.25×10^{1}	n/d	2.00×10^{-2}	5.40×10^{-3}
Zn	n/d	n/d	n/d	3.00×10^{-1}	6.00×10^{-2}
V	n/d	n/d	n/d	9.00×10^{-3}	9.00×10^{-3}
Fe	n/d	n/d	n/d	7.00×10^{-1}	1.40×10^{-1}
As	1.50	3.66	n/d	3.00×10^{-4}	1.23×10^{-4}
Hg	n/d	n/d	n/d	3.00×10^{-4}	2.10×10^{-5}
Cu	n/d	n/d	n/d	4.00×10^{-2}	1.20×10^{-2}

n/d (not detected).

Table A2. The constant values obtained from the literature and used in the risk formula.

Parameters	Distribution (Saha vd. 2017)	Mean	SD	Unit	Uncertainty Range
IR (daily intake rate) (L/day)	Log-normal	2.20	0.34	L	−30% to 10%
BW (body weight) (kg)	Log-normal	70	10.71	kg	−30% to 20%
SA (surface area of the skin (m^2)	Log-normal	1.8	0.092	m^2	−10% to 10%
EF (exposure frequency) (day/year)	Triangular	-	-	day	350 (180–365)
ET (exposure time)	Triangular	-	-	h	0.58 (0.4–0.7)
Kp (cm h^{-1})	Cd, Cr, As, Fe, Mn, Cu, V ve Hg 1×10^{-3} cm h^{-1}; Pb 1×10^{-4} cm h^{-1}; Zn 6×10^{-4} cm h^{-1}; Ni 2×10^{-4} cm h^{-1}; Co 4×10^{-4} cm h^{-1}	USEPA, 2011. Risk assessment guidance for superfund. In: Part A: Human Health Evaluation Manual; Part E, Supplemental Guidance for Dermal Risk Assessment; Part F, Supplemental Guidance for Inhalation Risk Assessment, vol. 1.			
ED (Exposure Duration) (year)	considered 70 years for carcinogen and 30 years for others	Cr, Cd, As, Ni and Co are carcinogenic.			
AT (Average Time)	AT = 365 × ED				

Table A3. The averages of heavy metal values measured on a station basis.

Metals / Stations	Cr	Fe	Cu	Zn	Hg
1	n/d *	6.5	2.69	4.19	n/d
2	0.901	6.01	2.43	3.99	n/d
3	n/d	5.57	3.04	4.05	15
4	n/d	5.61	2.975	3.63	17.9
5	n/d	5.59	2.23	3.66	13.95
6	n/d	5.9	2.78	4.02	n/d
7	n/d	6.17	2.89	4.18	n/d
8	n/d	5.47	2.76	3.73	n/d
9	n/d	6.46	2.9	4.67	n/d
10	n/d	5.17	2.06	4.06	13.6
11	n/d	5.81	2.61	3.77	n/d

* n/d (not detected): It could not be measured because it was below the limit values of the measuring device. V, Mn, Co, Ni, As, Cd and Pb values could not be measured as they were below the limit values at all stations.

Table A4. The human health carcinogenic risk values.

Statistics		Wastewater Ingestion	Wastewater Dermal	Bilge Water Ingestion	Bilge Water Dermal	Sum of Row
Cr	MEAN	2.78×10^{-1}	5.07×10^{-4}	3.51×10^{-1}	6.35×10^{-4}	9.80×10^{-1}
	SD	3.89×10^{-1}	6.97×10^{-4}	3.98×10^{-1}	7.36×10^{-4}	7.89×10^{-1}
	95%	2.95×10^{-1}	5.32×10^{-4}	3.77×10^{-1}	6.80×10^{-4}	6.47×10^{-1}
Ni	MEAN	5.53×10^{-1}	1.26×10^{-2}	7.64×10^{-1}	1.76×10^{-2}	1.39×10^{0}
	SD	6.27×10^{-1}	1.39×10^{-2}	5.16×10^{-1}	1.17×10^{-2}	1.17×10^{0}
	95%	5.92×10^{-1}	1.33×10^{-2}	8.06×10^{-1}	1.86×10^{-2}	1.43×10^{0}
As	MEAN	1.12×10^{-1}	1.29×10^{-3}	1.06×10^{-1}	1.20×10^{-3}	2.21×10^{-1}
	SD	1.45×10^{-1}	1.61×10^{-3}	1.53×10^{-1}	1.73×10^{-3}	3.02×10^{-1}
	95%	1.21×10^{-1}	1.36×10^{-3}	1.13×10^{-1}	1.27×10^{-3}	2.37×10^{-1}
Sum of mean		9.82×10^{-1}	1.44×10^{-2}	1.22×10^{0}	1.95×10^{-2}	2.24×10^{0}
Sum of 95%		1.01×10^{0}	1.51×10^{-2}	1.27×10^{0}	2.06×10^{-2}	2.31×10^{0}

Table A5. Non-carcinogenic risk values for human health.

Statistics		Wastewater Ingestion	Wastewater Dermal	Bilge Water Ingestion	Bilge Water Dermal	Sum of Row
Cu	MEAN	0.0137676	0.0002062	0.0132393	0.000201	0.0274141
	SD	0.023401	0.0003501	0.0213641	0.0003258	0.045441
	95%	0.0147042	0.0002186	0.0139733	0.0002122	0.0291083
Fe	MEAN	0.0048907	0.0001108	0.0035096	0.000083721	0.0085947
	SD	0.0089712	0.0002109	0.0082978	0.0001897	0.0176696
	95%	0.0052676	0.0001161	0.0036923	0.000087992	0.009164

Table A5. *Cont.*

Statistics		Wastewater Ingestion	Wastewater Dermal	Bilge Water Ingestion	Bilge Water Dermal	Sum of Row
V	MEAN	n/d	n/d	0.8832509	0.0040042	0.8872551
	SD	n/d	n/d	1.5450067	0.0070964	1.5521031
	95%	n/d	n/d	0.9503096	0.0043296	0.9546392
Cr	MEAN	1.5938608	0.0071553	2.5847651	0.0121605	4.1979417
	SD	4.188305	0.0191794	4.7227134	0.0216054	8.9518031
	95%	1.6869873	0.0074531	2.8437182	0.0130773	4.5512359
Mn	MEAN	n/d	n/d	0.0595795	0.0016197	0.0611993
	SD	n/d	n/d	0.1261246	0.0034331	0.1295577
	95%	n/d	n/d	0.0627949	0.0017668	0.0645617
Co	MEAN	2.3599987	0.0281829	1.5710246	0.0149318	3.974138
	SD	3.4128698	0.0251617	2.8270833	0.0256707	6.2907855
	95%	2.5563837	0.0299013	1.6919398	0.0156585	4.2938832
Ni	MEAN	0.0594741	0.0001952	0.0335937	0.0001138	0.0933768
	SD	0.1267451	0.00043	0.0948059	0.0003226	0.2223036
	95%	0.0642419	0.0002052	0.0354411	0.0001242	0.1000124
Zn	MEAN	0.0037113	0.000048516	0.0057477	0,000083186	0.0095908
	SD	0.0066415	0.000090762	0.0071425	0,000096470	0.0139712
	95%	0.0039896	0.00005116	0.0062195	0,000086554	0.0103468
As	MEAN	2.7818464	0.0341568	2.9126479	0.0326103	5.7612614
	SD	5.6162113	0.0622389	5.5312011	0.0622638	11.271915
	95%	3.0538807	0.0357044	3.0963149	0.0344657	6.2203658
Cd	MEAN	0.0241106	0.0056022	0.0357484	0.0082488	0.07371
	SD	0.035465	0.0080373	0.0334968	0.0076138	0.0846128
	95%	0.0254578	0.0058554	0.0381872	0.0088543	0.0783547
Hg	MEAN	n/d	n/d	3.2346663	0.2038807	3.438547
	SD	n/d	n/d	6.8524151	0.4456866	7.2981017
	95%	n/d	n/d	3.3915152	0.2157773	3.6072926
Pb	MEAN	0.3546892	0.0004249	0.4727835	0.001375	0.8292725
	SD	0.7098101	0.0008595	0.8127913	0.0023161	1.525777
	95%	0.3761364	0.0004584	0.5045601	0.0014653	0.8826202
Sum of mean		7.1963494	0.07608275	11.81055	0.27931269	19.36230
Sum of 95%		7.7870493	0.07996371	12.638666	0.29590572	20.801585

n/d (not detected).

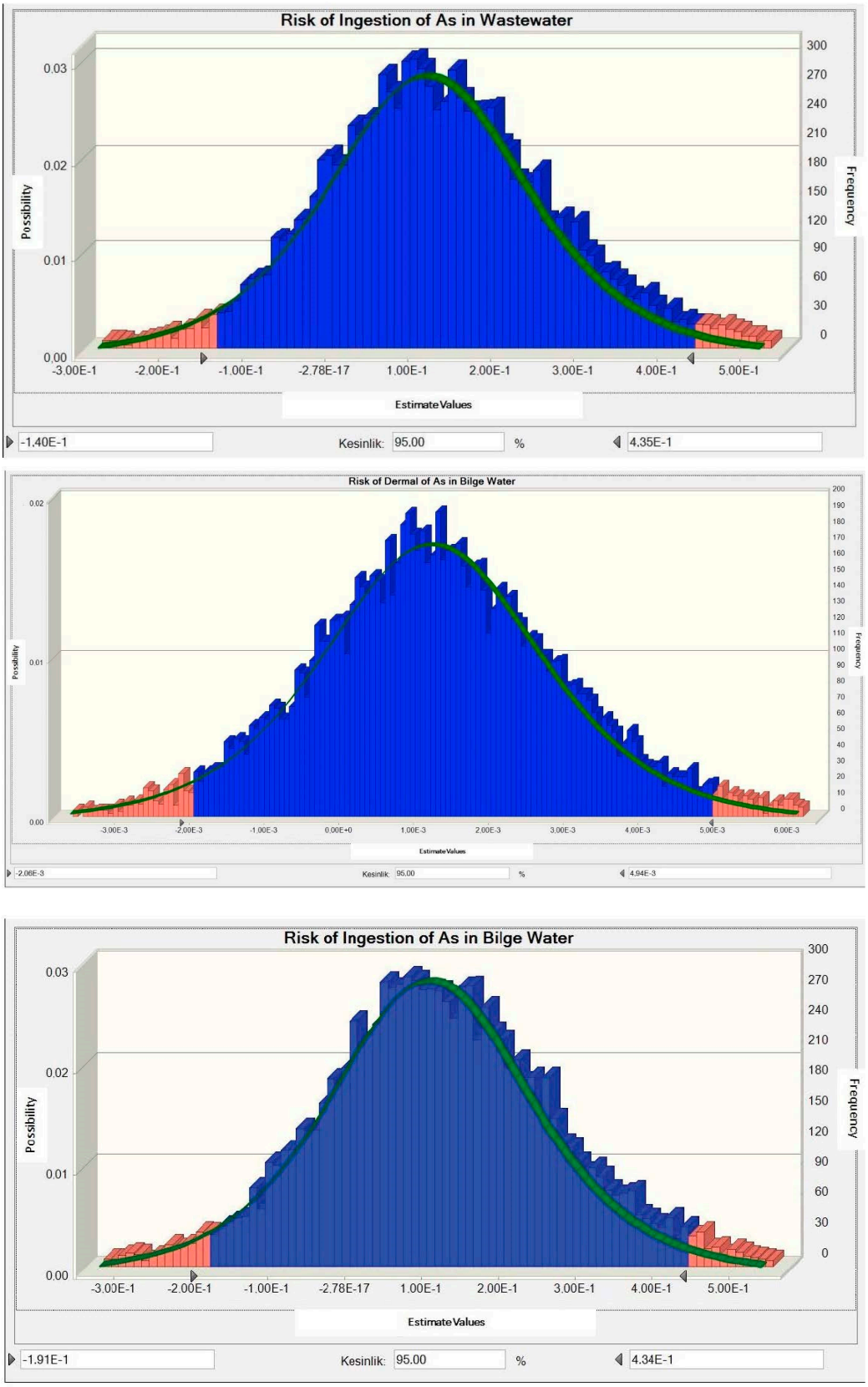


Figure A1. *Cont.*

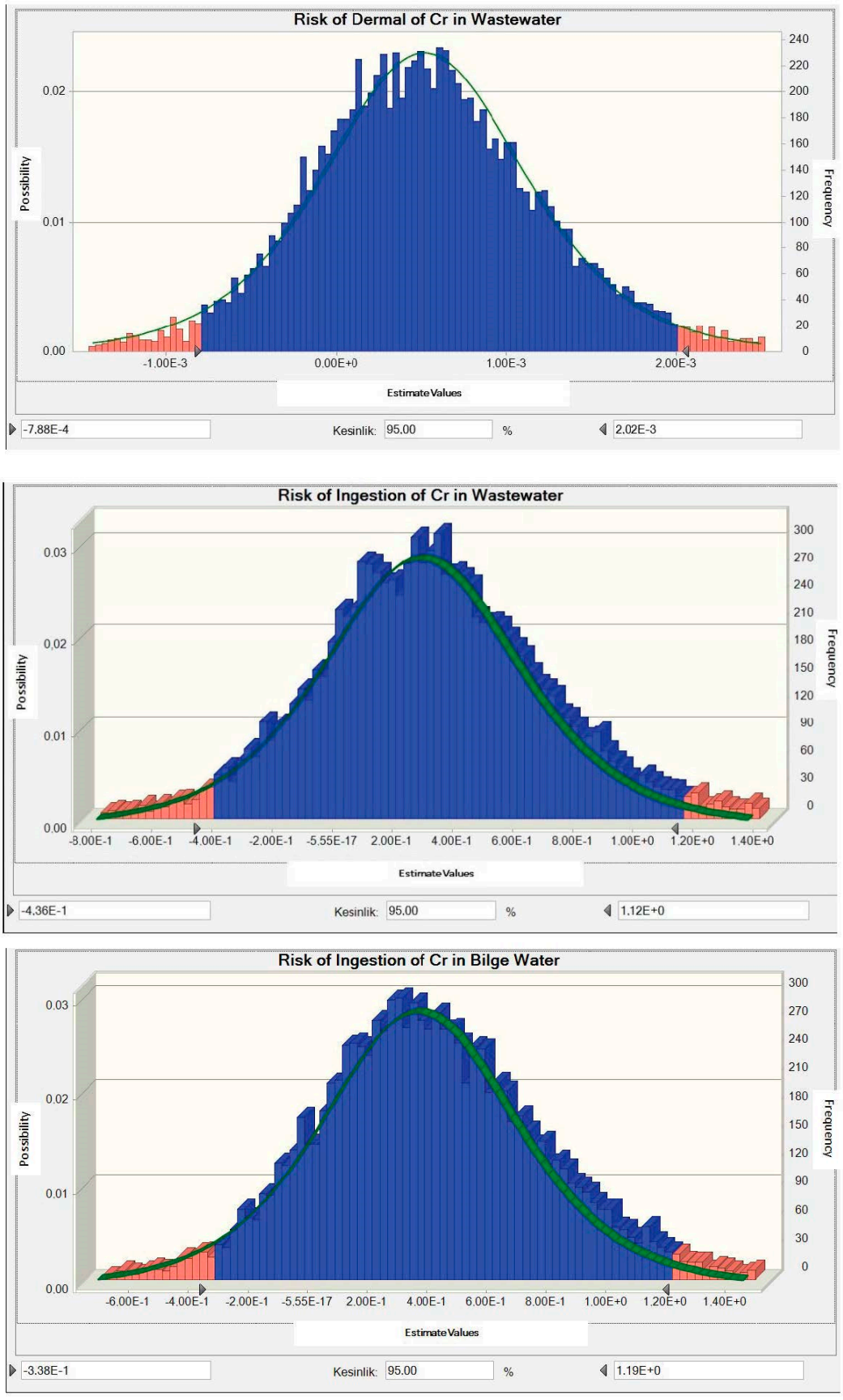


Figure A1. *Cont.*

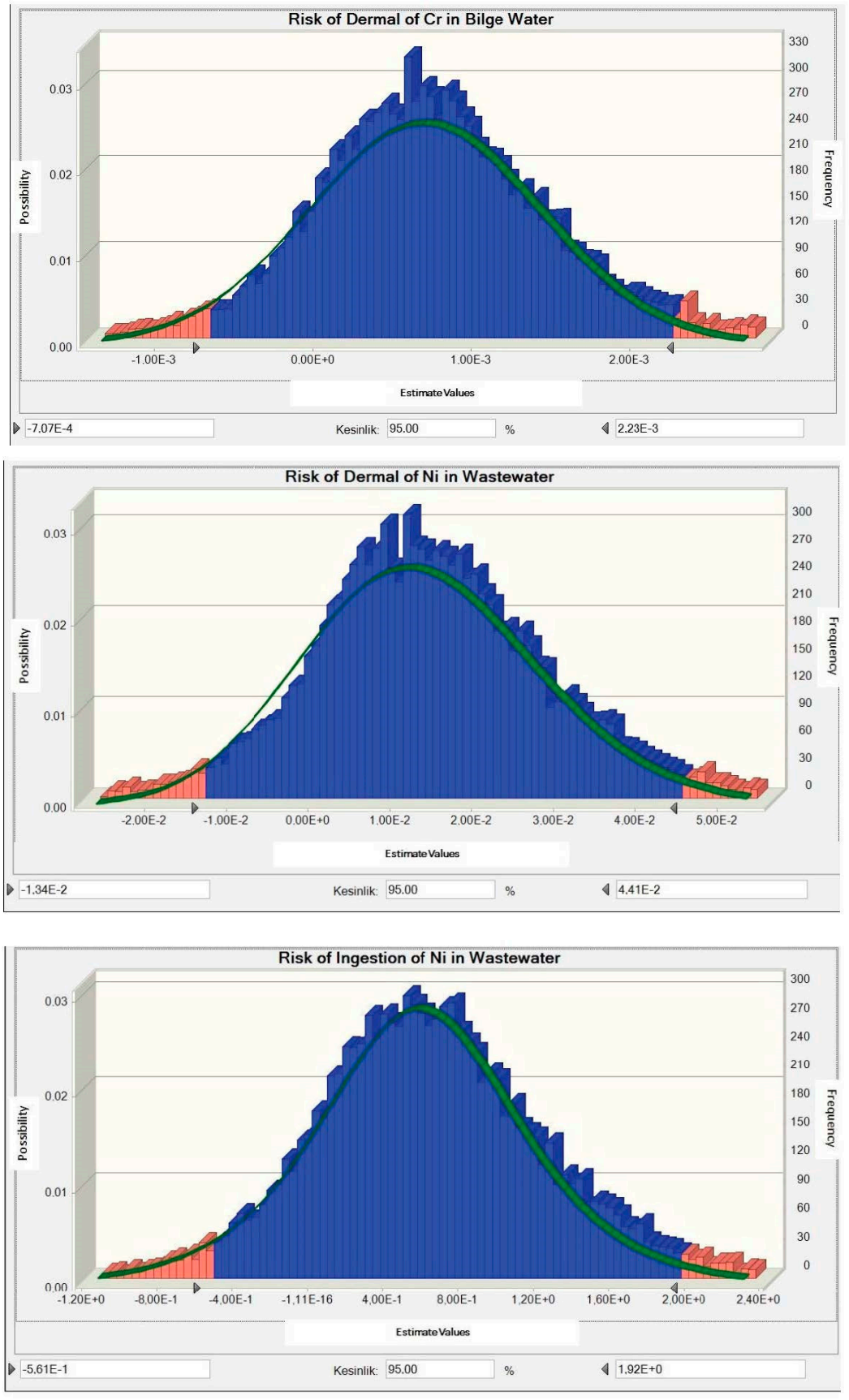


Figure A1. *Cont*.

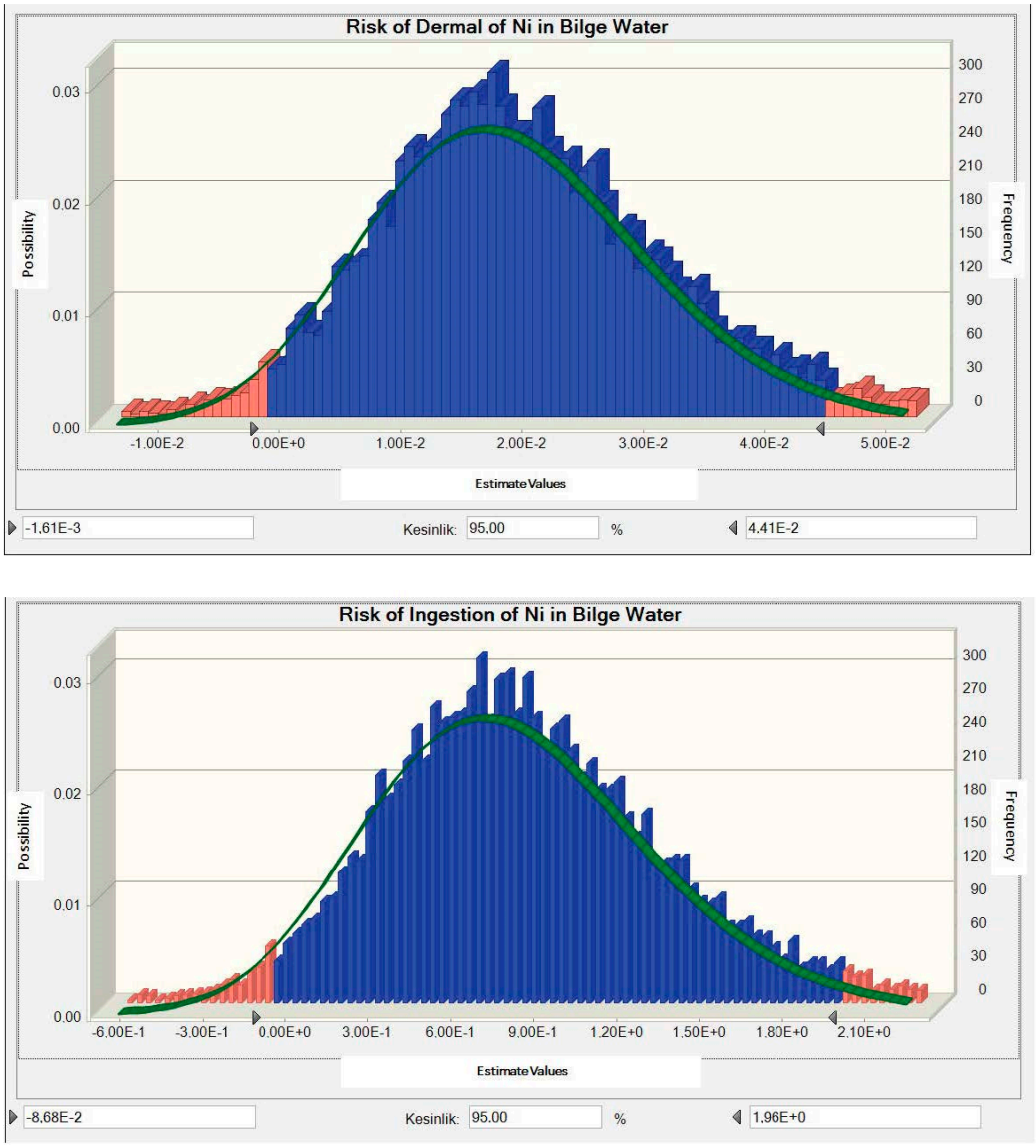


Figure A1. MCS risk distribution graphs of other heavy metals.

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Climate Change Adaptation Strategies and Its Impact on Household Vulnerability to Food Insecurity: A Micro-Level Evidence from Southwest Ethiopia

Andualem Begashaw [1,*], Mengistu Ketema [2], Abule Mehare [2], Mesay Yami [3], Shiferaw Feleke [3] and Tahirou Abdoulaye [3]

[1] Department of Economics, Mizan Tepi University, Mizan Aman P.O. Box 260, Ethiopia
[2] Ethiopian Economics Association, Addis Ababa P.O. Box 34282, Ethiopia; mengistuket@gmail.com (M.K.); abule.mehare@gmail.com (A.M.)
[3] International Institute of Tropical Agriculture (IITA), Headquarters & West African Hub, Ibadan P.O. Box 5320, Nigeria; m.gurmu@cgiar.org (M.Y.); s.feleke@cgiar.org (S.F.); t.abdoulaye@cgiar.org (T.A.)
* Correspondence: andutg24@gmail.com; Tel.: +251-913-651-246

Abstract: Smallholder farmers in Ethiopia face increasing challenges from climate change and variability, which threaten their food security and livelihoods. This study examines how adopting single and combined climate change adaptation practices affects their vulnerability to food insecurity in Bench Maji Zone, southwest Ethiopia. Through multistage sampling, data were gathered from 390 rural households in four climate-prone districts. The study examines the impacts resulting from both individual and combined implementations of adaptation techniques. These techniques encompass crop management practices, soil and water conservation measures, and livelihood portfolio diversification strategies. The study employed the multinomial endogenous treatment effect regression model to address selection bias and endogeneity resulting from various sources of heterogeneity, whether observed or unobserved. The results show that farmers who adopted adaptation practices were less vulnerable to food insecurity than those who did not. The study also finds that adopting multiple practices has a more significant impact than adopting single practices. Our findings suggest that implementing climate change adaptation strategies can increase the resilience of smallholder farmers in the study area and decrease their vulnerability to food insecurity. The study recommends supporting farmers in adopting these strategies through research and development, information dissemination, and collaborations among farmers, researchers, and extension services.

Keywords: climate change adaptation; food insecurity; vulnerability; multinomial endogenous treatment effect; smallholder farmers; Ethiopia

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1. Introduction

It is widely agreed upon that the global climate has undergone significant changes and will continue to do so. The IPCC's Sixth Assessment Report (AR6) offers vital information about the physical science underpinnings of climate change. According to the report, human activity raised the average global surface temperature during the pre-industrial era. From 1850–1900 to 2010–2019, the global surface temperature has increased by 0.8 °C to 1.3 °C, with the most accurate estimate being 1.07 °C [1]. It is crucial to comprehend the far-reaching impacts of global warming on the delicate balance of the planet's climate and environmental systems. Rising temperatures are expected to lead to more frequent severe weather events like droughts, storms, and floods. Additionally, ripple effects could include disruptions in ocean currents, altered rainfall patterns, and a worrisome rise in sea levels [2].

The impacts of global climate change are felt differently across the world, with developing countries bearing the brunt due to their limited capacity for climate change adaptation,

technology, and resources [3,4]. Food security remains a pressing issue in developing nations, including Ethiopia, where instability and fluctuations persist due to various factors such as shocks, environmental threats, and resilience to challenges. Households in these regions face unpredictable access to food as a result of natural disasters and economic shocks [5,6]. Understanding the dynamic nature of food insecurity is essential for policymakers and researchers to devise effective strategies and interventions to enhance food security in these vulnerable areas. The resilience of households to cope with and recover from these events plays a crucial role in determining the availability and accessibility of food.

The World Food Programme [7] has reported a distressing surge in the number of Ethiopians requiring humanitarian food assistance. It is estimated that 15.4 million people have been impacted due to ongoing instability and climate-related disruptions. This crisis is expected to continue, resulting in a prolonged period of heightened need throughout 2024. The vulnerability of Ethiopia's rural livelihood systems, which rely on agricultural, pastoral, and agropastoral systems, to climate change is a pressing concern. Rainfall is a primary climatic factor that significantly influences food production and access in Ethiopia since the agricultural system relies mainly on rainwater rather than irrigation [8].

Adaptation strategies play a vital role in ensuring the sustainability of agriculture in Ethiopia, especially in the face of climate change. The ability of farmers to adapt to environmental and economic challenges is key to building resilience in the agricultural sector. Farmers' ability to adapt to environmental and economic disturbances is essential for the resilience of the sector [9]. Limited adaptation skills among farmers can result in economic setbacks. According to the [10] characterization, smallholder farmers in Ethiopia typically cultivate less than 2 hectares of land. They engage in mixed farming, involving both crop production and animal husbandry, and heavily rely on family labor for agricultural tasks. Due to their limited access to modern agricultural inputs, technology, and extension services, their output is primarily for subsistence, with a minimal surplus for commercial purposes. Additionally, the [10] report highlighted that Ethiopian smallholder farmers are particularly susceptible to external shocks such as market fluctuations, diseases, pests, and climate variability. To combat the adverse effects of climate change and variability, smallholder farmers and local governments are implementing various strategies, such as soil and water conservation, crop diversification, and livelihood diversification. These strategies are aimed at reducing vulnerability to food insecurity.

Despite the importance of adaptation strategies, there has been a lack of comprehensive analysis of their impact on farmers' vulnerability to food insecurity. Up to now, far too little attention has been paid to analyzing the impacts of different adaptation strategies to climate change and variability on farmers' welfare in a rigorous fashion. Few studies have primarily focused on examining the impacts of individual or single adaptation practices, such as crop diversification or soil and water conservation [11–13]. While these studies have greatly enhanced our understanding of adaptation and its impact on farmers' well-being, they fail to consider a range of complementary, alternative, and supplemental approaches to address climate change and variability. Moreover, [14] highlighted that farmers often employ a combination of strategies to cope with climate variability and argued for the importance of analyzing the synergistic effects of these practices. Similarly, [15] noted that adopting a single adaptation strategy may be insufficient and emphasized the need to consider the joint impacts of complementary adaptation measures. Therefore, ignoring the likely interrelationships between the various strategies in adoption and impact analysis may lead to biased conclusions [16].

Few studies have explored the impact of adaptation practices on farmers' welfare in Ethiopia, utilizing a variety of adaptation strategies [17,18]. However, these studies often fail to delve into the specific areas of adaptation to climate change, resulting in limited insights into the effectiveness of different strategies. Neglecting the diverse adaptation strategies and capacities across different contexts and locations can lead to inaccurate conclusions regarding the true impact of these measures [19].

Against this backdrop, this study focuses on examining how various adaptation practices influence household vulnerability to food insecurity at the micro level. By evaluating both individual and combined adaptation strategies, this research aims to offer a comprehensive understanding of farmers' adaptation behaviors and their implications for food security.

The results of this study hold significant potential to inform policymakers, development organizations, and international research initiatives about crafting more targeted and effective adaptation strategies for the agricultural sector. By contributing valuable insights to the existing literature on climate change adaptation, this study sheds light on how farmers can adapt to the challenges posed by a changing climate. Through identifying the impact of adaptation practices on vulnerability to food insecurity, our research aims to enhance our understanding of sustainable adaptation measures within the agricultural sector, ultimately fostering resilience in the face of climate change. Additionally, the study can provide crucial information to policymakers and agricultural extension services, improving their comprehension of farmers' interpretations of climate change and the constraints that hinder them from implementing more robust adaptation measures. This understanding, in turn, will guide policymakers in promoting adaptation and developing a more participatory plan for climate change and variability. Furthermore, the study results will benefit non-governmental organizations (NGOs) and donor countries engaged in development activities by offering location-specific insights that may influence their development intervention approaches.

2. Materials and Methods

2.1. Research Design

The study employed a quantitative research design using cross-sectional data. Survey data were collected from smallholder farmers to assess the impacts of climate change adaptation practices on households' vulnerability to food insecurity. The survey covered adopters and non-adopters of climate change adaptation practices, using a non-experimental approach. To ensure the representativeness of the sample and wider generalizability of the results, we used a multi-stage sampling procedure involving both purposive and random selection. Data analysis was carried out using descriptive statistics and econometric models, such as a multinomial endogenous treatment effect (METE) model. This rigorous quantitative approach allowed us to generate robust, evidence-based findings that can inform policies and interventions to enhance the climate resilience of smallholder farmers.

2.2. The Study Areas

Bench Maji Zone is one of the zones in Southwest Ethiopia Peoples Regional State (SWEPR) that makes up the southwest part of the country and lies between 5.34–7.53° N latitude and 35.13–36.23° E longitude, covering about 19,326.59 km^2 (see Figure 1). The mean temperature in the zone typically ranges between 15 and 27 °C, making it moderate for the residents. Additionally, the average annual rainfall varies from 400 to 2000 mm, contributing to the environmental conditions of the area. According to the 2007 census projection by the Central Statistical Agency of Ethiopia [20], the estimated population size in 2018 is around 918,792 individuals. Among them, approximately 50.4% are female, highlighting the gender distribution within the zone. Moreover, a significant 87% of the population are rural dwellers, emphasizing the rural lifestyle prevalent in the area.

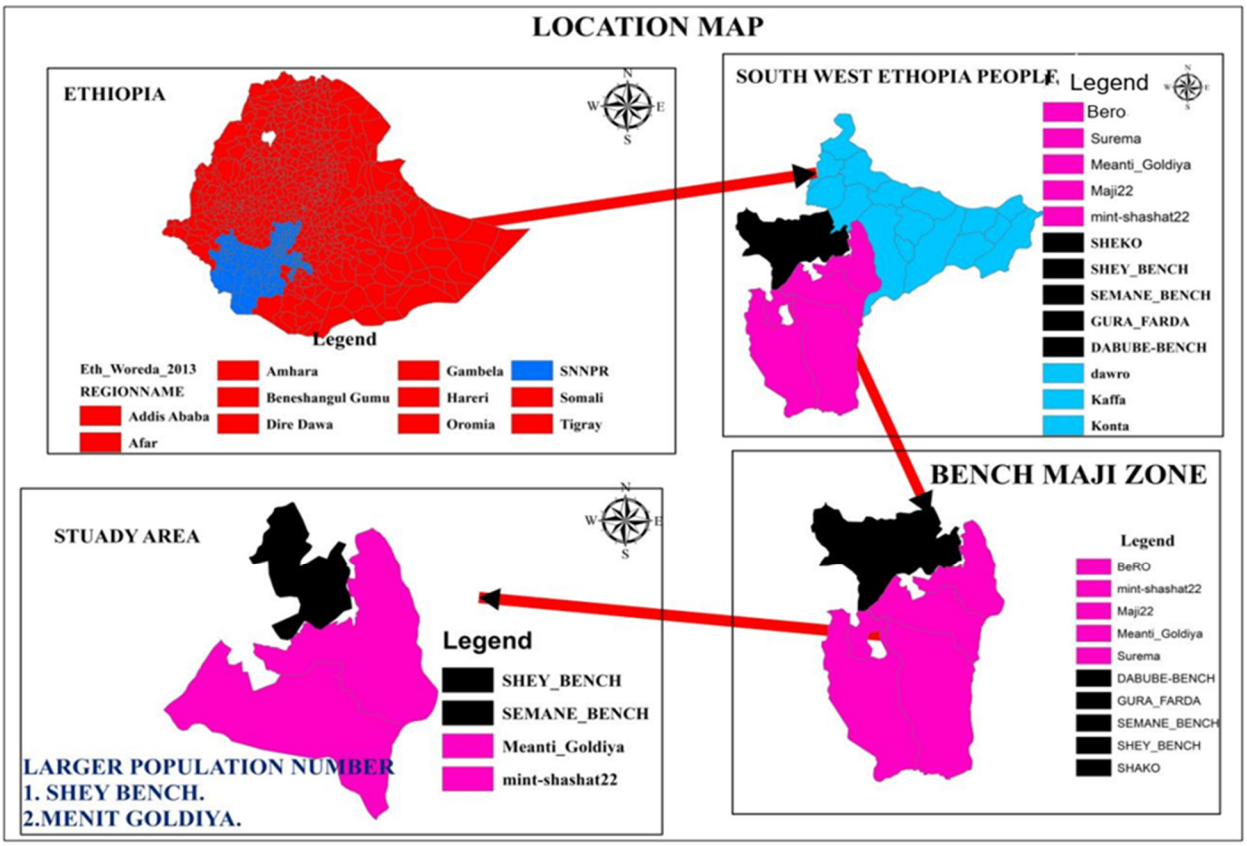


Figure 1. Map of the study areas.

Rain-fed agriculture is the primary sector that dominates the livelihood of the Bench Maji Zone, except for limited areas where traditional and small-scale irrigation methods are employed for vegetable cultivation. Agricultural activities encompass both crop cultivation and livestock production. Two distinct rainy seasons, Kiremt and Belg, are utilized to cultivate long-cycle crops. The Meher season is commonly defined as an extended period of precipitation, typically spanning from June to September. The term "Belg season" often denotes the short yet timely rainy season, typically observed between February and May, but in specific regions of the country [21]. Coffee, spices, and fruit crops are among the essential perennial cash crops in the zone. Among the annual crops, maize, sorghum, root crops, and tubers cover the bulk of crop production [22]. In the zone, the natural forest resource has been excessively utilized, leading to a rapid increase in deforestation and environmental degradation. This issue is closely intertwined with factors such as re-settlement, unplanned land use management, and unrestrained use of natural resources. The consequences of these actions are severe and far-reaching [23].

2.3. Data Collection and Sampling Technique

The study meticulously collected quantitative data to comprehensively examine how adapting to climate change and variability affects farmers' vulnerability to food insecurity. To determine the current household food insecurity status, we considered information about all the foods that the household bought with money, ate from their own farm or garden, or obtained from other people, such as friends, someone a family member worked for, or the government. To ensure the robustness and accuracy of the survey, a well-structured questionnaire with a mix of open-ended and closed-ended questions was developed and pilot-tested. Additionally, field training was conducted to familiarize the enumerators with the study's objectives and the farm household survey. The instruments focused on crucial areas such as past climate-related shock experiences, socioeconomic factors, crop and domestic livestock practices, land ownership, agricultural resources, access to institutional

services, climate change and variability awareness, existing adaptation strategies, and food consumption and spending. Secondary materials were also reviewed to complement the primary data and identify any existing gaps.

This study employed a rigorous multistage sampling method, which combined both probability and non-probability techniques, to identify the most appropriate districts, kebeles, and households. In the initial phase, four districts, namely Semen Bench, Shey Bench, Menit Goldiya, and Menit Shasha, were deliberately chosen from the districts of the Bench Maji Zone due to their high vulnerability to climate-related threats such as crop pests, livestock diseases, food production shortages, seasonal flooding, and recurrent landslides [23]. For the second stage, four kebeles (A kebele is the smallest administrative unit in Ethiopia's decentralized government structure. It is typically a named peasant association and is considered the lowest level of government administration in the country.) were randomly selected from the Semen Bench district, three from the Shey Bench district, four from the Menit Goldiya district, and three from the Menit Shasha district based on their distribution in each sample district. In the third step, 390 farmers were randomly selected as a representative sample using the probability proportional to the sample size sampling technique based on the number of farm households in Kebeles.

In line with the methodology suggested by [24,25], this study utilized the following formula to ascertain the minimum sample size required for a representative sample from the known population:

$$n = \frac{Z^2 * p(1-p) * N}{e^2(N-1) + Z^2 * p(1-p)}$$

The sample size computation for the selection of households from each district took into account (i) a 5% margin of error (e = 0.05) at 95% confidence (Z = 1.96); (ii) N = 84,980; (iii) the proportion (p) for the different variables under investigation (p = 0.88). Moreover, to be consistent with many previous studies of this type [26–28], which factored in a design effect ranging from 1.5 to 2.5, this calculation has also considered a design effect of 2.5 to address the multistage sampling inherent errors. Additionally, a 5% non-response rate (NRR) has been accounted for to accommodate households that may be unavailable, inaccessible, uncooperative, or have any other hindrance preventing survey teams from reaching the selected household.

2.4. Methods of Data Analysis

2.4.1. Theoretical Framework

This study used a random utility framework to analyze how climate change adaptation strategies impact household vulnerability to food insecurity. The model is framed on the principle that an individual derives utility by choosing some alternatives [27,29]. The model assumes that a farm household will only adopt an adaptation strategy if the benefits exceed those of not adopting it. However, the utility derived from adaptation is not directly observed but inferred through the farmers' choices. The standard formulation of the linear random utility model is as follows:

$$U_A = \alpha_A{}' Z_i + \varepsilon_A$$

$$U_N = \alpha_N{}' Z_i + \varepsilon_N$$

Relevant explanatory variables represented by Z_i influence the perceived utility of adaptation. The parameter estimates for choosing an adaptation strategy and not adapting are $\alpha_A{}'$ and $\alpha_N{}'$, respectively. The correlation of error terms of the adaptation equations determines the type of qualitative choice model used in the analysis. This implies that a household i will decide to adapt to climate change and variability if

$$A^* = E(U_{iA}) - E(U_{iN}) > 0$$

where $E(U_{iA})$ and $E(U_{iN})$ are the expected utility of implementing the strategy and not adapting, respectively.

2.4.2. Analytical Techniques for the Impact of Adaptation to Climate Change

This study utilizes a multinomial endogenous treatment effect (METE) model to examine the impact of climate change adaptation strategies on a household's vulnerability to food insecurity. The model has two stages [30]. In the first stage, farm households face choices regarding climate change adaptation practices. We introduce the latent variable G^*_{ij}, representing expected welfare outcomes (vulnerability to food insecurity), when adopting the climate change adaptation strategy j ($j = 1 \ldots J$) instead of another strategy (k):

$$G^*_{ij} = X_{ij}\varphi_j + \sum_j^J \delta_i l_{ij} + \varepsilon_{ij} \quad (1)$$

X_i represents factors affecting strategy ***j***, such as household and plot characteristics, market access, climate change perception, and shock variables. The parameter φ captures the impact of each factor on the adoption decision, while the error term ε_{ij} accounts for unobserved characteristics and $E(\varepsilon_{ij}|X_i) = 0$. Additionally, a latent factor l_{ij} considers the hidden characteristics that influence decision-making, such as farmers' technical knowledge and managerial skills in adapting to climate change (Abdulai and Huffman 2014).

In line with [30], we define $j = 0$ as nonadopters, with $G^*_{i0} = 0$ remaining unobserved. Instead, binary variables $d_i = (d_{i1,} d_{i2,} d_{i3,} \ldots, d_{iJ})$ are employed to determine responses to climate change, while corresponding latent components $l_i = (l_{i1,} l_{i2,} l_{i3,} \ldots, l_{iJ})$ influence the choice of adaptation strategies. The probability of adopting strategies is expressed as:

$$P_r(d_i|X_i l_i) = g(\acute{X}_i\varphi_1 + \sum_j^J \delta_{1j} l_{ij} + \acute{X}_i\varphi_2 \sum_j^J \delta_{2j} l_{ij} \ldots + \acute{X}_j \varphi_j \sum_j^J \delta_{Jj} l_{ij}) \quad (2)$$

If g confirms a mixed multinomial logit (MMNL) structure and represents an appropriate ate multinomial probability distribution:

$$P_r(d_i|X_i l_i) = \frac{\exp(\acute{X}_i\varphi_j + \delta_i l_{ij})}{1 + \sum_{j=1}^J \exp(\acute{X}_i\varphi_j + \delta_i l_{ij})} \quad (3)$$

In the second stage, the METE model assesses how climate change adaptation practices impact vulnerability to food insecurity [31,32], represented by the expected outcome equation:

$$E(VFI_i = 1|z_i, d_i, l_i) = z_i\vartheta + \sum_{j=1}^J d_i\gamma + \sum_{j=1}^J l_i\tau \quad (4)$$

This equation considers exogenous covariates z_i, parameter vectors ϑ, and the impact of adaptation strategies on vulnerability to food insecurity (VFI) relative to non-adaptation, denoted by parameter γ. Additionally, the factor-loading parameter (τ) influences the correlation between climate change adaptation strategies and outcomes, where a positive value suggests positive selection and a negative value indicates negative selection [30,32].

For the METE model to be identified, [30] recommends using at least one selection instrument that affects the adaptation decisions of farming households but does not affect the outcome variables among the households. However, finding an instrumental variable is tedious and challenging in empirical analysis [11]. A simple falsification test was conducted on the excluded instruments, i.e., climate change perception [17,33,34]. Through this test, the instrument (climate change perception) influences the adoption of climate change adaptation strategies in all cases, but not consumption per adult equivalence. The model estimation utilized the mtreatreg command within the Stata software package 15. This particular command ensured the precise and accurate estimation of the model.

2.4.3. Assessing Household Vulnerability to Food Insecurity

This study adopts the Vulnerability as Expected Poverty (VEP) approach to assess households' vulnerability to food insecurity. This approach estimates the likelihood of households experiencing food insecurity using consumption expenditure per adult equivalent (FCEAE) as an indicator of household well-being [35]. Household vulnerability to food insecurity, denoted as $V_{h,t}$, indicates the likelihood of a household falling into poverty in the following time $(t+1)$ period due to consumption, such that:

$$V_{h,t} = \Pr(C_{h,t+1} \leq ‡) \tag{5}$$

where $C_{h,t+1}$ represents the welfare indicator level of household (FCEAE) h at time $t+1$, and ‡ is the food poverty line, indicating the value of food necessary to meet the recommended minimum daily calorie requirement of 2200 kilocalories per adult equivalent.

The FCEAE of the household can be expressed as a function of observed and unobserved characteristics:

$$\ln C_h = X_h\beta + \varepsilon_h, \tag{6}$$

X_h represents a set of observable household characteristics, and ε_h is a mean-zero disturbance term that captures personal factors affecting per-capita food consumption. The variance of the unexplained portion of FCEAE ε_h contingent upon the household's farm and socioeconomic characteristics:

$$\sigma^2{}_{\varepsilon,h} = X_h\theta + \omega_h \tag{7}$$

where θ represents a vector of parameters that need to be estimated, ω_h is the vector of residuals of this second estimation. To address heteroscedasticity, a three-step feasible generalized least squares (FGLS) method is employed to obtain consistent estimates of β and θ. The variance of the idiosyncratic element of household consumption is estimated as:

$$\hat{\sigma}_{\varepsilon,h} = \sqrt{X_h\hat{\theta}_{FGLS}} \tag{8}$$

This variance is used to define the homoscedastic consumption function in Equation (9), and the predicted log household food spending per adult equivalent per day is estimated using Equation (10).

$$\frac{\ln C_h}{\hat{\sigma}_{\varepsilon,h}} = \frac{X_h}{\hat{\sigma}_{\varepsilon,h}}\beta + \frac{\varepsilon_h}{\hat{\sigma}_{\varepsilon,h}}$$

$$\ln C_h{}^* = X_h{}^*\beta + \varepsilon_h{}^* \tag{9}$$

$$\hat{E}\{\ln C_h | X_h\} = X_h\hat{\beta} \tag{10}$$

The variation in each household's log food consumption expenditure is as follows:

$$\hat{\psi}\{\ln C_h | X_h\} = \hat{\sigma}_{\varepsilon,h} = X_h\hat{\theta} \tag{11}$$

Assuming that food consumption per adult equivalent is log-normally distributed [36], we can determine each household's probability of food insecurity at a future time

$$\hat{V_h} = \hat{P}(\ln C_h < \ln ‡ | X_h) = \varnothing\left(\frac{\ln ‡ - \ln X_h\hat{\beta}}{\sqrt{X_h\hat{\theta}}}\right) \tag{12}$$

where $\varnothing(.)$ indicates the log-normal distribution of food consumption expenditures. Based on the vulnerability coefficient $\hat{V_h}$, households can be categorized as vulnerable or non-vulnerable. Households with a vulnerability coefficient of 0.5 or higher are considered at risk of food insecurity [6]. This study follows a consistent procedure for categorizing vulnerable and non-vulnerable households based on their vulnerability coefficients.

The study uses 2200 kcal per day per adult as the food poverty line, the minimum energy requirement for a nutritionally adequate essential diet [37]. Household food insecurity is identified when the money spent on food is insufficient to meet this daily dietary need. Thus, households are considered food insecure when their food expenditure is inadequate to purchase a nutritionally adequate diet. This approach provides insights into households' vulnerability to food insecurity based on their consumption expenditure and the likelihood of falling below the minimum energy requirement in the future.

3. Results

3.1. Descriptive Results

Table 1 presents the features of sample households according to socioeconomic factors and the strategies they have adopted to adapt to climate change. Notably, households headed by men comprised 78% of adopters, with women making up the remaining 22%. There were 8.14% non-adopters and 91.86% adopters among the 86 households headed by women. The table also shows that 38 percent of the sample as a whole had yet to complete any form of education. Nearly half of the entire sample (48 percent) achieved a primary level of education, and those who attained senior secondary education represent around a quarter of the sample respondents.

Table 1. Characteristics of sample households: categorical variables.

Variables	Description	Adopters		Nonadopters		Chi-Square Test (χ2)
		Number	%	Number	%	
Gender	Male	273	77.6	7	18.4	0.32
	Female	79	22.4	31	81.6	
Level of Education	No formal Education	127	36.1	22	57.9	7.54 **
	Primary	174	49.4	14	36.8	
	Secondary	51	14.5	2	5.3	
Off-farm Activity	Yes	157	44.6	13	34.2	1.51
	No	195	55.4	25	65.8	
Access to Credit	Yes	174	49.4	18	47.4	0.06
	No	178	50.6	20	52.6	
Extension Contact	>=6	209	59.4	17	44.7	3.02 *
	<6	143	40.6	21	55.3	
Membership	>2	139	39.5	15	39.5	0.001
	<2	213	60.5	23	60.5	
Climate Information	Yes	116	33	17	44.7	2.12
	No	236	67	21	55.3	
Good soil	Yes	168	47.7	16	42.1	0.44
	No	184	52.3	22	57.9	
Moderately fertile soil	Yes	115	32.7	18	47.4	3.29 *
	No	237	67.3	20	52.6	
Flat plot slope	Yes	170	48.3	15	39.5	1.07
	No	182	51.7	23	60.5	
Moderately plot Slope	Yes	103	29.3	16	42.1	2.67
	No	249	70.7	22	57.9	
Severity of soil erosion	High	180	51	10	26.3	8.46 **
	Low	172	48.9	28	73.7	
Perceived climate shock	Low	121	34.4	25	65.8	14.53 ***
	Medium	167	44.4	10	26.3	
	High	64	18.2	3	7.9	

Source: Own survey (2022). ***, **, and * indicate statistical significance at less than 1%, 5%, and 10%, respectively.

Furthermore, the data reveal a significant mean difference (at a 5% significance level) in education levels between adopters and nonadopters, with 36.08 percent of adopters and 57.89 percent of nonadopters having no formal education. This finding underscores the crucial role of education in climate change adaptation. Off-farm job opportunities are generally limited in the study area. Only 43.59% of sample households were employed

in off-farm activities, with 44.6% of adopters and 34.21% of nonadopters engaged in such activities.

A significant percentage of farmers (42.05%) did not have regular contact with extension service agents at least six times a year. On the other hand, a substantial proportion of 57.95 percent received regular technical advice and support at least six times a year. In the adopter group, 59.38 percent of respondents reached out to extension service agents at least six times per year, compared to 40.63 percent in the nonadopter group. There is a noticeable difference in the frequency of contact with the extension agents between the two groups.

Participation in socioeconomic groups serves as a powerful indicator of social capital endowment, a key factor in climate change adaptation. Forty percent of respondents were members of at least two socioeconomic groups, indicating a significant level of social capital. Among adopters, 39.5% belonged to at least two groups, while 60.5% did not. Similarly, 40 percent of nonadopters were also members of at least two groups. This fact emphasizes the importance of community involvement in climate change adaptation and the need to strengthen social capital for more effective adaptation strategies.

The survey asked participants whether they were entitled to early warning information and climate change-related content. The results revealed a significant disparity, with only 34.1 percent of households receiving this crucial information, while a staggering 65.9 percent were still in need. This lack of early warning information has had a profound impact, preventing households from appropriately anticipating and adapting to the effects of climate change and its variability.

Among the respondents, a significant disparity in perceptions of the impact of climate change was observed. Nearly half, 48.72 percent, of sample farmers perceived their plots as severely eroded, while the remaining 51.28 percent did not. Interestingly, 51% of adopters and 26% of nonadopters perceived their farms as severely eroded. This disparity in perception underscores the need for increased awareness and action. In terms of climate change impact, 34% of adopters and 68% of nonadopters were perceived as having a low impact, 47% of adopters and 26% of nonadopters had a medium impact, and 18% of adopters and 8% of nonadopters perceived a high impact.

Table 2 reveals a significant age difference between adopters and nonadopters, with adopters being older. Most respondents (96%) fell within the productive age range of 21 to 64, indicating their potential for active participation in climate change adaptation strategies. The youngest and oldest respondents were 21 and 71, respectively, with the average age of all respondents being 42 years. The mean family size of the sample population is 4.7, which is almost identical to the national average of 4.6 people per household [20]. Furthermore, the mean family size of nonadopters and adopters is 4.6 and 4.7, respectively.

The average number of animals owned by the sampled households, measured in Tropical Livestock Units (TLUs), is 3.5. Notably, nonadopters of climate change adaptation strategies have an average livestock ownership of 1.92 TLUs, while adopters have an average ownership of 3.71 TLUs. The statistically significant mean difference (less than 1%) in livestock ownership between adopters and nonadopters suggests that households with greater livestock holdings are more inclined to adopt adaptation strategies compared to those with fewer animals (Table 2).

Table 2. Characteristics of sample households: continuous variables.

Variables	Mean	Adopters	Nonadopters	t-Value
Age	42.5 (0.56)	42.6	41.8	−0.39
Family Size	4.7 (0.11)	4.7	4.6	−0.43
Livestock	3.5 (0.16)	3.7	1.9	−6.56 ***
Farm Size	1.4 (0.04)	1.4	1.3	−1.22
Distance to market	31.5 (1.14)	31.5	31.4	0.04
Climate perception	1.01 (0.02)	1.02	0.86	2.72 ***

Source: Own survey (2022). *** indicates statistical significance at less than 1%. The numbers in parentheses are standard errors.

In the study area, the average farm size for sample households is 1.42 hectares of farmland. Specifically, nonadopters' households have an average size of 1.28 hectares, while adopters' households have a slightly larger average size of 1.44 hectares. The mean perception value for the combined sample is 1.01. Notably, nonadopters have an average perception value of 0.86, while adopters exhibit a slightly higher average value of 1.02. These results highlight a statistically significant difference between adopter and nonadopter households at a 1% significance level, emphasizing the role of perception in shaping the adoption of climate change adaptation strategies.

3.2. Comparing Conditional and Unconditional Climate Change Adoption Strategies (%)

Table 3 provides a comprehensive view of the unconditional and conditional probabilities of the sample. Notably, around two-thirds of the farmers have implemented crop management strategies, 53% use soil and water conservation techniques, and 41% diversify their livelihood portfolios. The table also highlights the interdependence among these three strategies for adaptation. Specifically, about 70% of farmers who practice crop management also use soil and water conservation measures, and 47% have diversified their livelihood portfolios. It is worth noting that adopting soil and water conservation actions increases the likelihood of implementing crop management practices by 4%. Similarly, farmers who use crop management techniques are more likely to conserve water and soil (56%) and diversify their livelihood portfolios (42%). Notably, these strategies exhibit intricate interdependence, mutually influencing each other.

Table 3. Conditional and unconditional probabilities of adopting climate change practices (%).

	Crop Management Practice (A)	**Soil and Water Conservation Measures (S)**	**Livelihood Portfolio Diversification (L)**
$p\left(Y_j = 1\right)$	66	53	41
$p\left(Y_j = 1 \middle\| Y_A = 1\right)$	100	56	42
$p\left(Y_j = 1 \middle\| Y_S = 1\right)$	70	100	47
$p\left(Y_j = 1 \middle\| Y_L = 1\right)$	65	52	100
$p\left(Y_j = 1 \middle\| Y_A = 1, Y_S = 1\right)$	100	100	40.0
$p\left(Y_j = 1 \middle\| Y_A = 1, Y_L = 1\right)$	100	55	100
$p\left(Y_j = 1 \middle\| Y_S = 1, Y_L = 1\right)$	70	100	100

Note: $Y_j = 1$ is a binary variable representing the adoption status concerning choice j ($j = 1$ Crop management practice (A), soil and water conservation (S), and livelihood portfolio diversification (L)).

3.3. Assessing Food Insecurity Vulnerability in the Study Areas

This study assessed rural households for food insecurity vulnerability using a <0.5 or $\geq$0.5 score, categorizing them as vulnerable or non-vulnerable [38]. The assessment of food insecurity status involved comparing consumption per adult equivalent to the food poverty line. Households below the threshold were classified as food insecure. Table 4 exhibits the categorization of households by their vulnerability level and food security status. The study revealed that 65.3% of households in the study areas were vulnerable to food insecurity. Interestingly, those who have adapted to climate change (65.9%) exhibited lower vulnerability levels, whereas the remaining 34% of households still face a high risk. This result suggests that despite efforts to address climate change, some households still face food insecurity. It is important to note that even individuals who have embraced climate change may not be completely shielded from its negative impacts, as some other factors or limitations likely contribute to their vulnerability.

Table 4. Categorization of households by their vulnerability level and food security status.

Level of Vulnerability	Food Security Status				χ^2	Adoption Status	
	Food Insecure		Food Secure				
	No.	%	No.	%		Adopters (%)	Nonadopters (%)
Vulnerable	92	65.3	49	34.8		34.1	55.3
Not vulnerable	102	40.9	147	59.1	21.236 ***	65.9	44.7
Total	194	49.7	196	50.3		100.0	100.0

Source: own computation based on survey (2022) *** indicates statistical significance at less than 1%.

As per Table 4, it is apparent that out of the 196 currently food-secure households, a significant majority (around two-thirds of the total households) displayed a high level of food security. This figure indicates that these households are unlikely to experience food insecurity shortly, as they have reliable access to sufficient and nutritious food. This access, in turn, reduces the risk of food insecurity and its negative impacts on their overall well-being. However, the fact that around 25% of the food-secured households (49 out of 196) were found to be vulnerable to food insecurity, which is a cause for concern. Despite their current food security status, these households are more likely to experience food insecurity in the future. They may have limited or unstable access to food resources, which puts them at a higher risk of insufficient food intake or poor dietary quality. This potential future food insecurity among currently food-secure households highlights the need for immediate action to prevent the worsening of the situation.

3.4. The Impact of Climate Change Adaptation on Vulnerability to Food Insecurity

We focus on analyzing the impact of climate change adaptation strategies on vulnerability to food insecurity. However, we need to delve into the factors that affect adopting these strategies, which is the initial phase of the METE model. The estimation results for the first stage are included in Appendix A.

As previously stated, this study utilized the METE model to examine the correlation between adaptation practices and households' susceptibility to food insecurity. The findings are presented in Table 5. Simply put, numerous selection correction terms are significant at the 1% level. Implementing various climate change adaptation practices will impact nonadopters differently if they choose to implement them. The results indicate that implementing both individual and combined adaptation strategies substantially reduces the likelihood of experiencing food insecurity across various outcome measures. Farmers should adopt climate change adaptation strategies to reduce their vulnerability to food insecurity during unpredictable climate events.

The results, as shown in Table 5, show that the combined use of all the climate change adaptation strategies ($A_1S_1L_1$) and the adoption of crop management practices alone ($A_1S_0L_0$) both decrease the likelihood of vulnerability to food insecurity. The vulnerability reduction is 12% and 8% points lower, respectively, compared to non-adoption. Adopting soil and water conservation measures in isolation ($A_0S_1L_0$) also reduces the probability of vulnerability to food insecurity by 14%. These findings are particularly relevant for farmers in the study area, where climate change significantly threatens food security. This reduction demonstrates that implementing soil and water conservation measures can enhance the resilience of cropping systems against climate change-induced water stresses such as floods and droughts. These results confirm earlier findings by [39] for farmers in eastern Ethiopia that adopting soil and water conservation practices reduces the probability of farmers being food insecure, vulnerable to food insecurity, and transient and chronically food insecure.

Table 5. Multinomial endogenous treatment effect estimates of adoption impacts of climate change adaptation strategies on vulnerability to food insecurity.

Outcome Variable	Strategy Choice	Average Treatment Effects on the Treated (ATT)	
		Coefficient	Standard Error
Vulnerability to Food Insecurity	$A_1S_1L_1$	−0.12 ***	0.003
	$A_1S_0L_1$	−0.16 ***	0.004
	$A_0S_0L_1$	−0.16 ***	0.003
	$A_0S_1L_0$	−0.14 ***	0.003
	$A_1S_0L_1$	−0.15 ***	0.002
	$A_1S_1L_0$	−0.24 ***	0.002
	$A_1S_0L_0$	−0.08 ***	0.003
	Selection terms		
	$^{\lambda}A_1S_1L_1$	0.02 ***	0.0007
	$^{\lambda}A_1S_0L_1$	0.14 ***	0.0006
	$^{\lambda}A_0S_0L_1$	0.01 ***	0.0010
	$^{\lambda}A_0S_1L_0$	0.11 ***	0.0008
	$^{\lambda}A_1S_0L_1$	−0.09 ***	0.0007
	$^{\lambda}A_1S_1L_0$	0.23 ***	0.0007
	$^{\lambda}A_1S_0L_0$	0.02 ***	0.0008

*** denotes significance at 1% significance levels.

More importantly, the highest reduction in the probability of vulnerability to food insecurity (24% points) is realized through crop management practices combined with soil and water management measures ($A_1S_1L_0$). This result is probably because using inputs and resources, such as improved seed varieties, proper fertilizer application, and pest and disease management techniques, can significantly increase crop productivity. By implementing soil and water conservation practices like terracing, contour ploughing, and mulching, soil fertility is maintained, leading to healthier crops and higher yields. This increased productivity ensures a more stable food supply and reduces vulnerability to food insecurity. Previous studies [40,41] show that adopting different agricultural technologies would likely positively impact crop yield, consumption expenditure, food security, and alleviating poverty.

Livelihood portfolio diversification strategies ($A_0S_0L_1$) have been found to be effective in reducing vulnerability when implemented alone or in combination with crop management practices or soil and water conservation measures ($A_1S_0L_1$ or $A_1S_0L_1$). These strategies, both alone and in combination, have higher vulnerability reduction effects (16.9%, 15.2%, and 16.8% points, respectively) compared to other combinations. Hence, adopting climate change adaptation measures can improve crop production's environmental and economic aspects. This improvement allows farmers to spend more on food items than they would have if they had not adopted the practices.

4. Conclusions

Agriculture plays a vital role in alleviating poverty and fostering economic development in numerous agrarian economies, such as Ethiopia. However, it is extremely susceptible to the effects of climate change and variability, which greatly affect farmers' economic well-being. Ensuring the long-term viability of agriculture hinges on farmers' ability to adapt their production systems to address both environmental and economic obstacles and changes.

Existing studies have focused on individual adaptation practices, but there is a need to consider the interplay between different strategies for a more comprehensive understanding. This study aimed to estimate the impacts of climate change adaptation practices on smallholder farmers' vulnerability to food insecurity in the Bench Maji zone in southwest Ethiopia. A multinomial endogenous treatment effects approach is used to find out how different and individual adoption practices affect farmers' susceptibility to food insecurity.

The results of our analysis are not just theoretical but have practical implications for farmers and policymakers. We found that adopting climate change adaptation strategies, particularly combinations of strategies, can significantly reduce vulnerability to food insecurity. The most effective strategy, however, is a combination of crop management practices and soil and water management measures. This suggests that by using improved seed varieties, proper fertilizer application, pest and disease management techniques, and soil and water conservation measures, farmers can significantly increase crop productivity and reduce their vulnerability to food insecurity.

Our findings highlight the importance of livelihood portfolio diversification strategies in reducing vulnerability to food insecurity. When combined with crop management practices or soil and water conservation measures, these strategies have a significant impact on reducing vulnerability. By diversifying their livelihood activities, individuals can better withstand shocks and stresses that may impact their primary source of income. The results show that, in almost all cases, adopting a single or joint adaptation strategy significantly reduces the probability of vulnerability to food insecurity. Therefore, it is essential to encourage farmers to practice the existing climate change adaptation strategies on their farms to reduce susceptibility to food insecurity during uncertain climate change events. Strengthening the existing adaptation strategies by advising farmers to adopt a combination of adaptation measures, as the study found that joint adoption can further reduce the probability of vulnerability to food insecurity, is crucial. Offering guidance and training to farmers on how to effectively combine different adaptation practices, such as soil and water conservation, agronomic practices, and livelihood diversification, can help them maximize the benefits of adopting a mix of adaptation strategies. Additionally, creating an enabling environment to support adaptation is necessary, which includes promoting research and development, disseminating information and knowledge on climate change adaptation to farmers through extension services and other channels, and fostering collaborations between farmers, researchers, and extension service providers to facilitate the adoption of these strategies. Addressing the social, political, and institutional factors that may be contributing to food insecurity and working with policymakers to develop and implement supportive policies, programs, and institutional arrangements can further facilitate the adoption of climate change adaptation measures by farmers.

The findings of this study are drawn from cross-sectional and household-level data. However, incorporating panel and farm plot-level data analysis could provide more robust evidence on the impact of adaptation on households' vulnerability to food insecurity. This would enable better understanding of the short- and long-term effects of adaptation strategies. Thus, future research should explore the influence of different adaptation strategies on smallholder farmers' welfare across varying time frames.

Despite the primary data used and the relevant empirical models chosen and applied to estimate the results, we realize and acknowledge the limitations of this study. The most important limitation lies in the fact that measuring vulnerability to food insecurity solely based on the amount of money required to achieve the daily minimum dietary requirement does not consider the non-income factors that influence food security, such as availability, utilization, and stability of the food supply, as well as social, cultural, and environmental factors [42].

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Appendix A

Table A1. Mixed Multinomial Logit Model: Determinants of Multiple Adaptation Strategies.

Variable	Coef.	Std.Er	Coef.	Std.Err.	Coef.	Std.Err.	Coef.	Std.Er	Coef.	Std.Er
	A1S1L1		A0S1L1		A0S0L1		A0S1L0		A1S0L1	
gender	0.707	0.748	−0.211	0.792	−0.524	0.705	−1.080	0.708	−1.204 *	0.658
lnagehh	−0.130	1.154	2.218 *	1.201	0.397	1.097	0.456	1.111	−0.522	1.020
educhh	1.074 **	0.487	0.839 *	0.476	0.946 **	0.457	0.676	0.461	0.786 *	0.426
lnlivestock	3.927 ***	0.507	−0.312	0.325	0.651 *	0.343	0.301	0.322	−0.480 *	0.283
exte	0.637	0.606	1.025	0.660	0.774	0.604	−0.169	0.592	0.035	0.550
mseg	−1.073 *	0.616	0.142	0.631	0.708	0.583	−0.058	0.594	0.345	0.542
good__soil	−1.693 **	0.873	1.070	0.953	−0.395	0.829	−1.144	0.775	0.312	0.815
off_farm	0.934	0.595	−0.281	0.658	0.664	0.587	1.386 **	0.584	0.031	0.558
credit	−0.303	0.590	−0.501	0.620	−0.368	0.576	−0.051 ***	0.572	0.154	0.536
moderate_soil	−0.945	0.884	−0.617	1.010	−1.278	0.877	−2.545	0.882	−0.625	0.844
slope_flat	−1.164 *	0.620	0.351	0.626	0.652	0.589	−0.181	0.605	0.500	0.555
erosion	0.346	0.630	1.201 *	0.657	0.732	0.610	1.371 **	0.607	0.719	0.574
clmt_shock	0.590	0.455	0.651	0.476	1.045 **	0.441	1.158 ***	0.442	1.399 ***	0.423
adq	−0.168	0.165	−0.151	0.174	−0.183	0.162	−0.507 ***	0.168	−0.104	0.151
lndis_mkt	−0.189	0.297	−0.095	0.309	0.195	0.295	0.108	0.293	0.139	0.271
clm_inf	−0.390	0.613	−0.818	0.656	−0.443	0.595	−0.788	0.595	−1.114 *	0.580
lnclmt_perc	1.227 **	0.626	−0.466	0.602	−0.024	0.568	1.116 *	0.648	0.245	0.572
_cons	−3.011	4.432	−9.908 **	4.798	−3.672	4.249	0.064	4.235	1.279	3.913
Variable	**A1S1L0**		**A1S0L0**							
gender	−0.151	0.616	0.298	0.646						
lnagehh	−0.070	0.919	0.647	0.957						
educhh	0.824 **	0.390	−0.266	0.427						
lnlivestock	0.567	0.273	1.142 ***	0.298						
exte	0.489	0.499	0.442	0.516						
mseg	0.438	0.489	−0.273	0.512						
good__soil	−0.098	0.723	−0.865	0.754						
off_farm	0.653	0.495	0.295	0.511						
credit	0.110	0.481	0.517	0.498						
moderate_soil	−1.127	0.749	−0.833	0.765						
slope_flat	1.514 ***	0.501	0.722	0.515						
erosion	2.040 ***	0.526	0.231	0.547						
clmt_shock	0.670 **	0.385	0.977 **	0.396						
adq	−0.220	0.137	−0.331 **	0.141						
lndis_mkt	−0.149	0.241	0.094	0.254						
clm_inf	−0.428	0.497	−0.386	0.509						
lnclmt_perc	0.924 *	0.508	1.495 *	0.580						
_cons	−0.478	3.532	−2.228	3.700						

Note: ***, **, * Significant at 1%, 5%, and 10% probability level, respectively. Source: Model results.

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Practices to Improve the Sustainability of Australian Cold Storage Facilities

Angus McLay [1], Gavin Morant [1], Kelilah Breisch [1], John Rodwell [2,*] and Scott Rayburg [1]

[1] Department of Civil & Construction Engineering, Swinburne University of Technology, Hawthorn, VIC 3122, Australia; srayburg@swin.edu.au (S.R.)
[2] Department of Management & Marketing, Swinburne University of Technology, Hawthorn, VIC 3122, Australia
* Correspondence: jrodwell@swin.edu.au

Abstract: With the ever-increasing threat of climate change and global warming, ways to make energy intensive buildings, such as cold storage warehouses essential for food preservation, more sustainable need to be found. Some refrigerated warehouse owners may be unaware or unsure of the benefits obtainable from implementing sustainable practices and technologies. To search for innovations that could inform the owners and managers of cold storage warehouses about how to enhance their sustainability, convergent interviewing of subject matter experts was conducted. The resulting practices and processes were organized into a hierarchy that ranged from essential to best practices that can be implemented to improve the sustainability of refrigerated warehouses. Examples of these practices and technologies include ideal refrigeration systems, racking methods, and insulation types. To encourage the use of sustainable practices and technologies, more reporting on successful or unsuccessful applications of practices and technologies needs to be communicated. Applying change diagnostic tools such as convergent interviewing enables a practical and industry focused set of outcomes to be determined that can help drive change towards more sustainable cold storage warehouses in Australia.

Keywords: logistics; management innovation; refrigerants; Montreal protocol

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1. Introduction

With a trend of rising global temperatures, accompanied by record-breaking CO_2 emissions, it is becoming ever more urgent to find means of reducing climate-altering emissions [1]. To facilitate this endeavor, over 100 countries have recently communicated or adopted new Nationally Determined Contributions (NDCs) and adopted net-zero target pledges with the aim of limiting global warming [2].

One underappreciated source of global emissions, where the focus is often on energy generation, is food production and waste. Food loss and waste are important because they contribute around 8 to 10 percent of global greenhouse gas emissions [3]. In 2019, it was estimated that around one-third of all food produced was never eaten, with all of the resources, energy, and consequent emissions that went into producing that food also being wasted [3,4].

With around 40 percent of the annual food produced worldwide requiring refrigeration, cold storage is important for perishable goods such as fruit, vegetables, and meat [5–8]. Cold storage warehouses are internationally regarded as one of the best ways to store perishable goods [9]. The global expansion of cold storage facilities is important to ensure food quality is preserved [10]. The strategic positioning of post-harvest infrastructure, such as cold storage, could help preserve food after harvest and reduce food loss [11].

A lack of cold storage facilities in the vicinity of farmers can result in a loss of produce after harvest [7], and spoiled food has been assessed as leading to 420,000 deaths per year [12]. The use of refrigeration systems for food storage will help reduce food

waste and, in turn, improve the global hunger situation [13]. Hence, cold storage is an important part of reducing global emissions from food waste while also combating global hunger and improving human health outcomes. However, this focus on addressing hunger and reducing emissions is not the first time cold storage has been the focus of climate change efforts.

1.1. Cold Storage Warehouses at the Core of the Most Successful Environmental Change Ever

Although the food implications of refrigeration are substantial, historically, perhaps the most well-known environmental issues associated with refrigeration are the global warming impacts of refrigerant emissions. The use of refrigerants such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) depleted the ozone layer, allowing harmful UV radiation to more easily penetrate to the earth's surface, contributing to a rise in global temperatures [14]. The discovery of the depletion of the ozone layer resulted in a decision to phase out the use of CFCs through mechanisms such as the 'Montreal Protocol' [15]. The Montreal Protocol was passed in 1987 with the aim of ending the use of ozone-depleting substances [16,17].

Initially, the Montreal Protocol called for a 50 percent reduction in the use of CFCs and some halons [15]. However, amendments to the protocol called for the total phase-out of CFCs and several HCFCs [15]. Further amendments to the protocol led to HCFCs being targeted with a total phase-out by 2029 for developed countries and 2040 for developing countries, and then HFCs were targeted with an 85% reduction in developed countries by 2036 [18].

Although the initial focus of these efforts was on refrigerants with low ozone depletion potential (ODP) values rather than low global warming potential (GWP) values [15], over time the amendments have moved from a focus almost exclusively on ODP to a growing consideration of GWP, as summarized in Table 1. In the 21st century, the focus has shifted to phasing-in refrigerants with low ODP and low GWP values [14]. Fourth-generation natural refrigerants include ammonia, hydrocarbons, and CO_2, which have very low or zero GWP but may have other properties, such as flammability, toxicity, or requirements for higher operating pressures, that may limit their applicability in some situations [19].

Table 1. Refrigerant generations and their phase-outs (adapted from [18,20–22]).

Generation	Refrigerants	ODP/GWP	Phase-Out (Developed Countries)
1st	Chlorofluorocarbons (CFCs)	1/~10,000	1995
2nd	Hydrochlorofluorocarbons (HCFCs)	0.055/~3000	2029
3rd	Hydrofluorocarbons (HFCs)	0/>1500	85% reduction by 2036
4th (current)	Hydrofluoroolefins (HFO)/Natural	0/>150	

Note: ODP = ozone depletion potential; GWP = global warming potential, expressed in CO2 equivalents.

Under the Kigali Amendment, actions under the Montreal Protocol are expected to prevent the emission of up to 105 billion tons of carbon dioxide equivalent greenhouse gases, helping to avoid up to 0.5 degree Celsius of global temperature rise by 2100—a truly unparalleled contribution to climate mitigation efforts and the single largest contribution the world has made towards restraining the global temperature rise [20–22]. The Montreal Protocol is considered to be one of the most successful environmental agreements of all time [20–22].

Despite the efforts to address the Montreal Protocol and its amendments, global and Australian demand for cooling has substantially increased. For example, the total refrigerant bank (amount in use) of HCFCs and HFCs in Australia, across all of the main forms of stock (e.g., stationary refrigeration, mobile air conditioning, refrigerated cold food chain, transport refrigeration, and domestic refrigeration), grew by 61 percent between 2006 and 2019 [19], despite the policies in place to phase out second and third generation refrigerants. Thus, while there are claims that the implementation of the Montreal Protocol

has been estimated to have delayed climate change by around 7 to 12 years [15], more work remains to be done to offset the climate impact of the growth in demand for refrigeration if global climate objectives are to be reached.

To address the climate impact of the growth in cooling demand in the cold storage sector, a major contributor to overall global cooling demand, refrigerant gases are only part of the solution. Many potential technological solutions exist to reduce cooling demand in cold storage warehouses, but in many cases, these are not being adopted. The slow uptake of improvements in the sustainability of cold storage may be due to a lack of knowledge on the part of cold storage companies or uncertainties as to what the best options are to reduce the impact of the growing refrigeration demand.

1.2. Drivers of Sustainability beyond Refrigerant Gases

There are a variety of drivers and possible drivers for the sustainability of cold storage warehouses. One driver is the nature of the gases in the refrigeration system, as discussed above, but other drivers include energy demand, especially due to warehouse volume and temperature, as well as insulation, flooring, the threat of frost heave, air and water infiltration, and the direct usage of greener energy sources such as solar arrays.

Cold storage warehouses are recognized as using a substantial amount of energy [23]. Among the systems driving energy usage in cold storage warehouses, the energy requirements of refrigeration systems are quite significant, consuming around 80 percent of the energy in the warehouses [6]. In broad terms, warehouse volume and the temperature set are key drivers of energy consumption for chilled storage and, more strongly, for frozen storage [24]. Studies have called for the evaluation of the energy effects of utilization, storage, and renewable energy supply in warehouses, considering the context of the facility and its characteristics [25].

Interventions to improve energy consumption could make substantial impacts on the amount of energy used, with possibly a 30% to 40% improvement through a combination of 'optimizing store usage', 'repairing [existing] equipment', and 'retrofitting energy-efficient equipment' [26]. Energy efficiency improvements could be obtained by investing in technology and/or by inexpensive maintenance or management practices [23].

Technologies such as racking, rack loaders, and their associated equipment are a good starting point for improving the sustainability of warehouses [27]. In turn, more advanced and comprehensive systems, such as automatic storage and retrieval systems, can optimize storage and picking processes by enabling densification, adaptability, and modularity [28].

Maintenance and operational practices also play a role, with some facilities running at an excessively low temperature, presenting an opportunity for cost-effective and straightforward temperature adjustments [26]. Yet such approaches are contested, with recent studies of the wider supply chain suggesting that lower-temperature cooling in the cold storage warehouse may lead to sustainability improvements [29]. Other operational practices, such as lot-sizing decisions and the behavior of the operators (e.g., with regard to opening doors), have received little attention, with the focus typically being on technological issues [23]. Research has been called for to investigate which and which combinations of these technologies and practices could optimize warehouse sustainability [28].

In terms of more specific improvements, addressing issues such as insulation thickness and type, age of the facility and refrigeration system, and door open times could reduce energy demand even further [24]. Table 2 summarizes the main types of insulation used in cold storage warehouses along with three of their key properties—thermal conductivity, moisture resistance, and fire safety.

Table 2. Summary of common insulation properties (Source: Authors' summary across: [30–32]).

Insulation Type	Thermal Conductivity	Moisture Resistance	Fire Safety
Fibreglass batts	Low	Low	Medium
Polyisocyanurate (PIR) panels	Medium	Medium	Medium
Expanded polystyrene (EPS) panels	Medium	Low	Medium
Extruded polystyrene (XPS) panels	Medium	High	Medium
Mineral wool	Medium	Medium	High
High-density polyurethane (PUR) foam	Medium	Medium	Low
Vacuum-insulated panels	High	Low	Low

The most commonly used of these types of insulation is expanding foam, where the foam is the core between two polymer composite or metal skins. Foamed polyurethane, expanded polystyrene, and polyisocyanurate are created by blending chemicals in a liquid state along with foaming agents, but since 2016, the use of polystyrene for new and many existing buildings has been phased out due to fire risk concerns [33]. Despite being one of the simplest considerations, the characteristics of insulation have more complexity than may be expected, as do many of the drivers of the sustainability of cold storage warehouses.

Similarly, flooring is a fundamental component of any construction, providing the foundational structure upon which the building is assembled. Cold storage warehouses require specialized flooring solutions to ensure consistent internal conditions are unaffected by the external environment. Any compromise to the integrity of the foundation may significantly undermine the functionality and efficiency of a cold storage facility. In particular, insulating the floors of cold storage warehouses originates from a need to mitigate heat flow and prevent frost heave [33].

Frost heave occurs when a temperature gradient develops in freezing soil, and examples include deformation of embankments, pipe ruptures, and building inclination [34]. For cold storage warehouses, after several months of operation, the underside of the floor slab may reach 0 °C. The increase in volume caused by the ice within porous materials such as soil displaces the ground surface through an upward movement. Structural integrity can be compromised when the slab cracks and shifts due to frost heave, which may also cause other structural members to shift, leading to devastating and costly consequences [33].

1.3. Air and Water Infiltration

Infiltration can lead to increased energy usage and moisture entry, which affect product quality. Air and water infiltration is particularly concerned with two main sources of infiltration: short intensive periods when a door is open (e.g., when transferring stock) and ongoing seepage.

There are two sets of doorways to consider: internal doorways and external doorways, as well as the use of anterooms as buffering zones between external air and water and internal areas. Minimizing door opening duration and other technologies and practices may vary depending on the location and purpose of the doorway as well as the frequency with which it is used [24].

Anterooms, also known as airlocks or vestibules, provide a physical barrier and transition area between external and internal environments [35]. The purpose of an anteroom is to buffer the thermal load and moisture content from the opening of the external door before the internal door into the cold storage warehouse is opened [36]. The smaller volume of anterooms allows them to promptly return to optimal temperatures after the external door's operation, further safeguarding the main storage area [37]. The added layer of protection anterooms provide ensures that energy usage remains optimized, the risk of moisture intrusion is minimized, and the longevity and quality of stored products are maintained [36].

Another technology or practice that could improve the sustainability of cold storage is through the usage of renewable energy sources. For facilities that often have a large roof surface area, a key option is the use of solar (photovoltaic/PV) arrays. Similarly,

load-shifting is another technique that could impact energy usage, or at least energy costs. In a typical residential home, load-shifting could be simply setting the dishwasher to a timer around 12 p.m. or shifting clothes washer and dryer cycles during the day.

However, many of the issues raised above may be proxies for other indirect effects on sustainability. For example, the age of the building may sometimes be a proxy for whether or not solar arrays are able to be mounted on the roof. The structural design of roof-mounted solar panel arrays must be able to support the weight of the mounts and panels as well as additional loads, such as electrical systems and other attachments, and be able to withstand the associated forces from winds [38]. Many commercial buildings may lack the structural capacity to support a roof-mounted PV array of significant size due to being constructed to meet only the minimum requirements [39].

Thus, although there is recognition that cold storage warehouses are a critical area where sustainability improvements could have a large impact on climate change, the wide range of issues that may impact the sustainability of cold storage warehouses may be holding back improvement efforts. Consequently, there need to be investigations into the mix of possible practices and technologies applicable to cold storage warehouses that could lessen the extent of climate change. Such efforts to search for management innovations entail determining and choosing the best practices and technologies.

1.4. Management Innovations and Best Practices

In the face of global climate change, political and social pressures, and regulatory requirements to improve sustainability, the cold storage warehouse industry is building on earlier efforts, such as their responses to the Montreal Protocol, to continue to improve their sustainability. Large numbers of organizations in the cold storage warehouse industry want to improve their sustainability and are adopting innovations, a trend that is generating "bandwagon" pressures [40]. Those pressures are for management innovations, particularly innovation in the management practices, processes, and structures that affect day-to-day work at an operational level where observable changes take place [41].

Bandwagon pressures to improve sustainability can come from regulations, both international and national, as well as from related industry and government bodies. To find innovations that can improve their performance, such as in terms of sustainability, managers engage in a process of a search [42] to close a performance gap and, at the operational level, try to generate and implement new practices, processes, structures, or techniques [43]. Such innovations are new to the company implementing them and are typically incremental in nature [41].

Searching for management innovations often becomes a search for best practices, which usually involves investigating the internal processes of best-in-class firms, industries, or competitors to become more competitive [44]. The idea is to benchmark against other organizations so that underperforming organizations can implement such "best" practices to close a performance gap [45].

However, the term best practice is often overused or misused, and it may be the case that activities deemed to be best practices may not be [46]. For example, practices that have been adopted by a notable proportion of an industry may become a requirement of doing business in that industry but are not sufficient to provide a competitive advantage [47]. Similarly, practices that start out as best practices may enhance organizational performance for only a short period of time until competitors also implement those practices [48]. Such widespread practices may become necessary, but not sufficient, for improved organizational performance [49].

That is, there may be categories of practices ranging from the essential, commonplace and standard practices that have been widely adopted by organizations, that do not necessarily contribute to competitive advantage through to practices used by the best organizations, where the "best" practices are those that differentiate between good and bad performers [47]. Note, though, that the categorization of specific practices may change over time. For example, pursuing best practices through benchmarking may only be a way

of remaining on par with the practices adopted by other organizations [48], which then become necessary but not sufficient for superior performance (per [49]).

Efforts to represent the range or categories of practices as more of a continuum suggest that there are a variety of 'promising' practices that may or may not be best practices for some organizations [45]. The management innovations are new to the company implementing them [41], but they are not new to other organizations, which may be performing well. Consequently, to the organization looking at and for practices to adopt, those management innovations are only 'promising', not 'best', for a variety of reasons, including that they may need customization to the organization before the adopting organization experiences any improvements [45].

That is, searches for management innovations may surface a variety of practices and technologies that range from those that are necessary but not sufficient for high performance through to promising but unproven or less known practices. More specifically, to improve the sustainability of cold storage warehouses, organizations could benefit from the generation of practices that represent management innovations, particularly innovations in management practices, processes, and structures that affect operational activities [41]. Therefore, this study's research question is *"What practices and technologies could enhance the sustainability of cold storage warehouses?"*

Although the issues outlined above are relevant to cold storage warehouses worldwide, this study focuses on the cold storage warehouse industry in Australia. Australia has some unique challenges in the cold storage industry because it is a very large country that is sparsely populated and generally has a warm climate. That is, Australia is heavily reliant on freight to move goods around the country and, particularly, on a widely distributed network of cold storage warehouses to safely store and deliver goods to market. These characteristics of the Australian cold storage industry mean that it is a huge consumer of energy, with consequently large greenhouse gas emissions. Hence, the need to improve the sustainability of this industry is critical.

2. Materials and Methods

To investigate the above research question, an inductive, action-oriented, and change-oriented method was used—convergent interviewing. Convergent interviewing is a diagnostic method that has a history of being used to inform organizational change since the 1980s [50]. Action- and change-oriented programs often generate and focus on the issues that participants have in common in order to build on that common ground [51].

In this study, the convergent interviewing process of Dick [50] was followed. The major components of convergent interviewing are the selection procedure for interviewees, the interviewing technique, the analysis of each round of interviews, and the final issue analysis [52]. An outline of this process can be seen in Figure 1.

The focus of the convergent interviewing was the research question "What practices and technologies could enhance the sustainability of cold storage warehouses?" That key question was used in each of the interviews. Next, a list of experts in the field of sustainability in cold storage warehouses was generated. The sequence of interviewees was determined, following Dick [50], by setting the first interviewee as the person who was most expert on the specific research question being examined. To determine the second interviewee, the project steering group considered who on the list was the next most expert in the field but was as different as possible from the first person. These two interviewees formed the first round of interviews, where the interviewees were the two most expert in the field and were as different as possible from each other. Continuing this process generates the subsequent sequence of interviewees in each round, with rounds continuing until no new information is received from interviewees for two rounds.

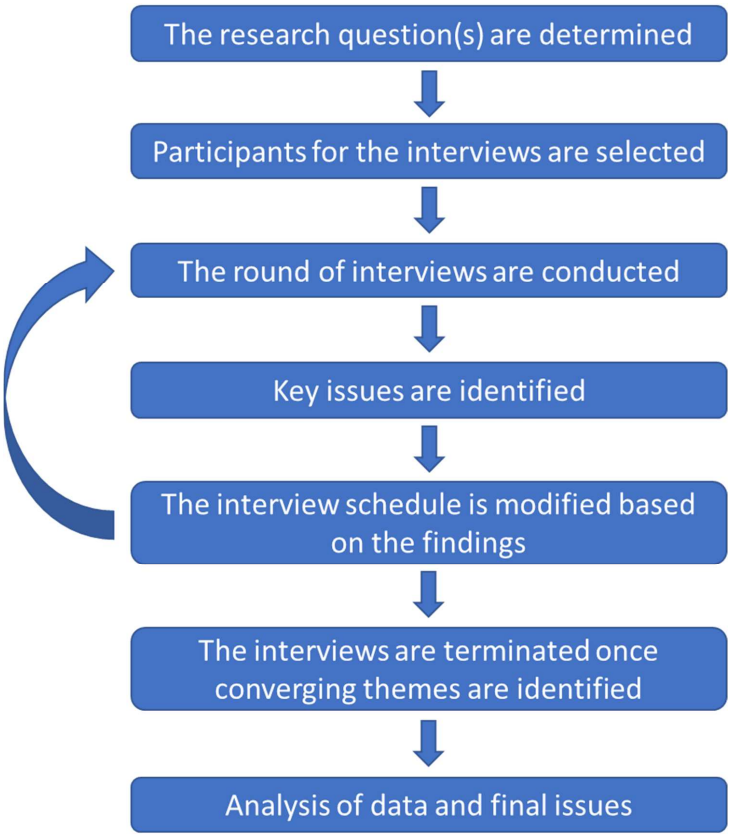


Figure 1. The process of convergent interviews.

The first round of interviews only asks one question (the primary research question), aiming to keep the interviewee talking for about an hour. The first round of interviews focused heavily on active listening and verbal and nonverbal cues to keep the candidate responding and to avoid leading the interview. All interviews began with this initial question across all of the rounds.

After each round, the project team analyzed the issues raised in the interviews and attempted to identify areas of agreement and disagreement among the interviewees; hence, the technique incorporates validation processes directly into the research strategy [53]. Issues arising in both interviews in a round, whether the interviewees agreed or disagreed, were part of the common results and were used to generate follow-up questions for later rounds of interviews. When both interviewees agreed on an issue, the probe question generated aimed to determine if there were circumstances when agreement may not occur. If interviewees disagreed on an issue, a probe question was generated to try to explore the reasons for the differences. Issues arising from just one interview were excluded from the analyses.

The probe questions generated after each round were designed to identify potential exceptions to the agreed-upon issues and explore differences between parties [51]. For example, the second round of interviews included probe questions such as "How can cold storage warehouses use space most efficiently?" and "What measures can be taken to limit air and water infiltration?" That is, as more interviews are conducted and additional data are collected, the interview questions are refined to highlight key insights [53]. The approach of the convergent interview is to have the interviewer intervene as little as possible to maximize the amount of time the interviewees speak.

The process is repeated until converging themes are identified [53]. Unlike many interview techniques, convergent interviews have a clear end point—when there have been two rounds of interviews with no new issues raised. The method is also considered flexible, with the subjective data obtained by it being overruled by its consistency in conver-

gence [54]. Ultimately, the primary advantage of convergent interviewing, as opposed to in-depth interviews, lies in its capacity to simultaneously and efficiently refine the content and the process of the interview, allowing common research issues to be focused on [53].

In this study, the team interviewed 10 candidates in five rounds. Not all of the experts interviewed were from Australia due to the niche pool of known experts for this project's specific question, but driving motivations for innovation were construed to be similar regardless of the country of origin of the interviewees. Almost all the interviews were conducted online using Microsoft Teams or equivalent software such as Zoom. After the impacts of COVID-19, the widespread familiarity of professional workers with remote work made setting up the virtual meetings easy and efficient, as candidates were familiar with the software and had the correct setups for a successful interview.

3. Results

The interview process confirmed that being energy efficient is critical for long-term sustainability and optimizing operational costs. The experts' insights can be condensed into two main categories: design and operations, with a secondary consideration being the considerations for new versus old buildings. The interviews revealed several considerations for cold storage warehouses, both new and existing, when trying to reduce energy consumption and emissions. The results are visually displayed in an affinity diagram (Figure 2) that shows the connections between the variables and components brought up by the experts.

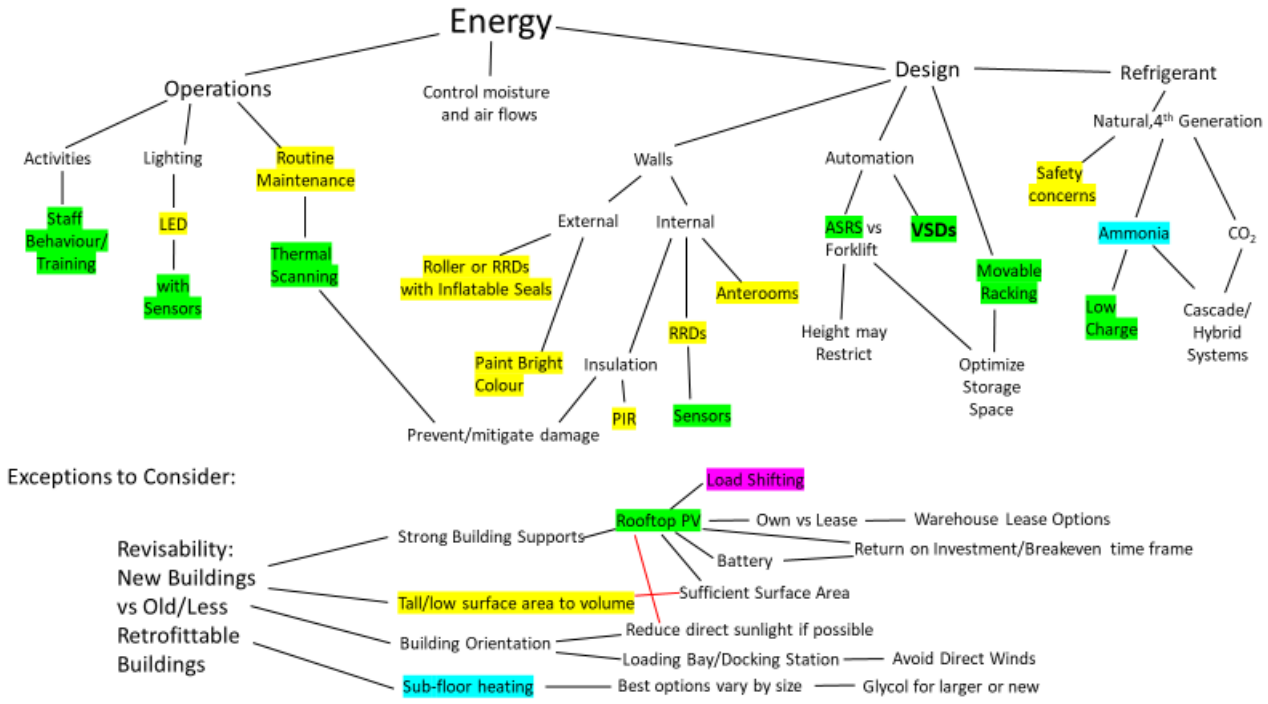


Figure 2. A detailed affinity diagram representing the main links between issues and practices in cold storage warehouses. Note: yellow highlighted practices are those considered essential by the experts; blue highlighted practices are those that are commonly accepted in the industry but often not exploited; green highlighted practices are those deemed best practices by the experts; purple highlighted text was identified as a "possible" best practice by the experts; red connecting lines indicate possible contradictory forces.

According to the experts interviewed in this study, many possible technologies and/or innovations have the potential to improve the sustainability of cold storage warehouses. Listed from those with the potential to have the largest to the smallest room for improve-

ment, given the current state of most of the industry, these topic categories of management innovations include:

- Refrigeration systems;
- Control and automation;
- Insulation;
- Air and water infiltration;
- Maintenance, monitoring, and operational practices.

3.1. The Refrigeration System

In their discussions of refrigeration systems, two important elements were raised by the interviewees. The first was the type of refrigerant used, and the second was the refrigeration system employed.

The interviews revealed that natural refrigerants are the most commonly used in industrial refrigeration systems. This is largely a result of the Montreal Protocol, which aims to phase out high GWP and ODP refrigerants that are harmful to the environment. Ammonia was the most common type of natural refrigerant in use in cold storage warehouses. Ammonia has the benefit of being the only refrigerant, alongside water and air, with a zero GWP and ODP [55]. Ammonia also has favorable thermodynamic properties, allowing it to absorb more heat than competing refrigerants [55]. An alternative refrigerant mentioned by the interviewees was carbon dioxide (CO_2), which, unlike ammonia, is not toxic or flammable. However, CO_2 has a low critical temperature, which is the temperature where a refrigerant in a gaseous state cannot be liquified [55]. Therefore, refrigeration systems using CO_2 as a refrigerant require high pressures, which can be expensive to design for as well as dangerous. That being said, CO_2 is often used in smaller commercial refrigeration systems and is also potentially useful in the lower-temperature stage of two-stage industrial refrigeration systems, as higher pressures are not required for these systems.

In terms of the refrigeration systems raised by the interviewees, only two came up as innovative: a pumped recirculated system using liquid overfeed and a low-charge ammonia direct expansion system. Of these, the interviewees suggested that the pumped reticulated systems are the most commonly used in cold warehouses. The interviewees attributed this to the fact that they have been used for decades in industrial applications and are therefore proven to suit larger applications. However, the experts said that direct expansion (DX) systems utilizing low-charge ammonia are the way of the future, particularly because, in every aspect of their functioning, they are superior to liquid overfeed systems, although they cost more up front (Table 3).

Table 3. Considerations for the two main refrigeration systems.

Ammonia Liquid Overfeed	Low-Charge Ammonia DX	
Lower	Higher	Capital cost
More	Less	Ongoing costs
Lower	Higher	Energy efficiency
More	Less	Emissions
Worse	Better	Safety

Per Table 3, low-charge ammonia DX systems are superior to ammonia liquid overfeed systems in terms of their ongoing costs, energy efficiency, emissions, and safety, but are less favorable in terms of up-front capital costs. Much of the improved performance across a range of indicators for low-charge ammonia DX systems stems from their improved energy efficiency. These DX systems tend to be more efficient than ammonia overfeed systems for two reasons. First, when operating, low-charge ammonia DX systems yield mostly vapor after the refrigerant exits the evaporator, which results in fewer energy-consuming pressure drops. Second, the absence of pumps in the DX system leads to further reductions in energy consumption compared to the ammonia liquid overfeed systems. Combined, these two

factors can lead to energy savings in the order of 15 to 30 percent per year. However, DX systems require more capital to implement due to design considerations, although the higher initial capital costs can generally be offset by energy savings in three to six years, regardless of whether they are retrofits or new systems.

Finally, low-charge ammonia systems are safer than liquid overfeed systems. One reason is that there is less ammonia in a low-charge system, and because ammonia is a toxic and flammable liquid, having less on premises lowers the risk of property damage and/or injury to workers. Given the improved qualities of low-charge ammonia DX systems across all critical measures, with the exception of upfront costs, and given the very short repayment period for these systems, it should only be a matter of time before they become the norm in the industry.

3.2. Control and Automation

Control and automation are areas where significant savings in energy use can be obtained in cold storage warehouses. The experts identified several technologies that help control and automate certain processes in refrigerated warehouses, including variable-speed drives (VSDs), sensors, automatic storage retrieval systems, and movable racking. The first of these technologies, VSDs, can vary the output of refrigeration system components such as compressors, condenser fans, and evaporator fans. Typically, refrigeration components are sized to meet the maximum cooling demand. Using variable-speed technology allows the refrigeration system components to operate at part load when the full cooling demand is not required, thereby consuming less energy. In contrast, traditional on-off operational methods cause large spikes in energy demand when components, such as compressors, are turned on. Further, VSDs reduce the likelihood of temperature fluctuations that can occur with traditional on-off methods, which can be damaging to some products.

The next automation and control technology identified by the interviewees was sensors. Temperature sensors in the cold rooms allow warehouse operators to monitor temperature fluctuations as well as identify any spaces that are underperforming. Temperature sensors can also monitor the external insulation to help identify leaks. Hence, sensors enable the warehouse to be run more efficiently and also to identify potential problems before they seriously impact the performance of the warehouse. Sensors are also used to operate rapid roller doors to minimize the time they remain open, thereby minimizing the intrusion of higher-temperature air into the warehouse. Another application for sensors in cold storage warehouses is to control lighting systems, with sensors used to turn on lights when required and to turn them off in areas not currently being accessed. A well-designed sensor system will be run by a control system using programmable logic control (PLC) to collect inputs from multiple sensor types and execute the desired commands without the need for human intervention.

The third control and automation system identified by the experts were automatic storage and retrieval systems (ASRSs). These systems are used to move stock around cool rooms without the need for direct human intervention. There are a few significant benefits to using ASRSs, which aim to improve energy efficiency and productivity. One benefit is being able to space-rack more closely, which increases the storage volume of each cool room where this technology is utilized. Additionally, having ASRSs allows racking to increase in height, as automated forklifts can reach items that a manual forklift cannot. By increasing the height of the racking, the surface area of the building can be decreased, which improves the energy performance of the warehouse. Another benefit of ASRSs is that they do not require lighting to operate. Therefore, heat generated by lighting is minimized, which reduces energy consumption.

The final control and automation technology identified by the interviewees was movable racking. Movable racking works by having the racking slide along rails to open an aisle, which a forklift can move down to collect pallets. Traditional warehouses have an aisle between each racking section, leading to a lot of unused space. Movable racking

helps reduce the unused space by increasing the density of the racking. Being able to move the racking allows for more storage space, which improves thermal performance and energy efficiency. When all of these technologies are employed, there is the potential to considerably improve the efficiency of cold storage warehouses, although they can also be implemented independently of each other, where each will yield improvements over traditional cold storage methods.

3.3. Insulation

Cold storage warehouses operate on the principle of maintaining internal temperatures vastly different from their external environment. Consequently, the energy consumption and overall sustainability of cold storage warehouses are heavily reliant on quality insulation practices and technologies in walls, roofs, and floors. Inadequate or compromised insulation poses a great risk of unnecessary and excessive air, water, and heat infiltration. By ensuring appropriate and robust insulation is provided, cold storage warehouses are able to drastically reduce their energy waste and maintain the consistent environment desired for the prolonged preservation of stored goods.

Walls and roofs are directly exposed to solar radiation, and insulation is the primary means by which the transfer of heat from the sun to the interior of the building is prevented. From the interview process, polyisocyanurate (PIR) insulation emerged as the ideal choice for cold storage walls and roofs in an Australian context due to its superior thermal performance, as shown in Table 4. PIR insulation also excels in safety, as evidenced by its commendable fire resistance, low smoke emissions, and minimal moisture absorption. These features not only ensure consistent insulation over time but also affirm PIR's superiority in terms of durability and longevity. Regarding its design and construction, although the ideal thickness of insulation is contingent on the desired internal temperature, external conditions, and energy efficiency targets, the experts suggested that 200–250 mm of PIR insulation provided the optimum thickness for insulating efficiency. Beyond this level of thickness, warehouse operators are expected to experience diminishing returns and excessive levels of initial investment costs.

Table 4. Heat flow for insulation materials [30–33].

Insulation Material	Density Kg/M^3	"K" Value W/mK at 10 °C Mean Temp.	Comment
Mineral wool slabs, fiberglass	24–28	0.028	Only applicable to 0 °C + temperatures.
Expanded polystyrene (EPS)	32	0.036	Fire risks.
Polyurethane sheets	36 ± 2	0.021	Most common globally.
Polyisocyanurate sheets (PIR)	32 ± 2	0.021	Increasingly used in Australia, but more expensive than substitutes.

Although PIR is superior to the main alternative insulation types, many warehouses have been built with other forms of insulation, often driven by the lower up-front cost of those alternatives. In such cases, the only option to rectify that issue would be to retrofit to PIR. Although this may seem like an attractive option given the benefits of upgrading, retrofitting has some serious drawbacks when it comes to insulation. These include the loss in time and opportunity in the period of the physical replacement of insulation panels, losses in cooling energy during the period when the insulation is being replaced, and the potential for stock losses if temperatures rise above safe levels during insulation replacement. Given these limitations, it is likely that PIR will be the insulation of choice for future builds, but that legacy insulation is likely to remain in place for buildings that were built using other forms of insulation. Given that, globally, cold storage warehouses frequently use polyurethane as their insulation material of choice [56], with many others using rockwool and extended/expanded polystyrene [57], it may be many years before PIR, an essential technology, is common.

Floor insulation in a cold storage warehouse has a different objective than wall and roof insulation. For walls and roofs, the insulation protects the interior of the building from external heating. In contrast, the purpose of floor insulation is to protect the underlying ground from penetration by the cold of the building because cold penetration into underlying soils can cause frost heave, which can damage the foundation and structure of the overlying warehouse. In Australia (where the climate is warmer), frost heave occurs less frequently than in other countries; however, prevention measures still need to be installed and are essential to the proper function of warehouses. Experts identified bulging sections, warped sections, uneven spots, cracking on walls and floors, and sinking floors at the corners of warehouses as identifiers of frost heave. To prevent frost heave, the floor temperature must remain above the freezing point of water, which can be accomplished by applying low-intensity and mild heat through pipes and vents underground, applying electric resistance heaters to the underside of the floor insulation, or suspending the floor [33].

3.4. Air and Water Infiltration

To improve the efficiency and sustainability of cold storage warehouses, another important consideration raised by the interviewees was air and water infiltration. Limiting the infiltration of air and water involves consideration of internal and external doorways as well as the use of anterooms. In this study, the experts drew attention to two main entrances to consider when addressing the issue of infiltration—dock doors and anterooms—and made clear distinctions in the considerations relevant for each of the two types of entrances.

For dock doors, roller doors were recommended due to the various benefits they provide over alternatives. For example, dock doors require high-speed and frequent operation during the transportation process, and roller doors are best suited to these conditions [58]. Not only do roller doors fulfill these requirements, but they also come with the added benefit of requiring less space to function than substitutes such as vertical and sliding doors. Furthermore, due to the sheer sizing requirements of such entrances, roller doors are the most appropriate door selection for ease of installation and ongoing maintenance. The experts agreed that the most suitable type of roller door to install are rapid roller doors (RRDs). RRDs are described as a premium version of typical roller doors, further excelling in speed, insulation, safety, and durability [58]. To further minimize excessive door opening times, it is recommended to fit such doors with motion door sensors to eliminate potential sources of human error. Motion detection devices allow goods to be transferred without compromising speed and acceleration on the approach and through the doorway, thus decreasing the necessary open-door time [59]. Alternative door types, such as strip and air curtains, were disregarded as best practices by the interviewees. Strip curtains are commonly found to be perceived as a nuisance to employees, consequently inciting practices such as tying the curtains up, effectively creating a permanently open doorway. Air curtains, on the other hand, were commonly reported as being excessively energy-consuming solutions with minimal return.

In conjunction with roller doors, the experts suggested that all dock doors be fitted with a form of air seal to ensure that truck doors align seamlessly with the warehouse dock. Inflatable seals were given as the most favorable solution because they are more flexible and accommodating of differing truck sizes and misalignments to the dock doors. Moreover, substitute products, such as flap seals, are prone to being snapped and broken when backing the truck up to the dock door. The combination of roller doors and inflatable seals minimizes the risk of ambient air infiltrating the warehouse.

Finally, anterooms were identified by the interviewees as useful means to reduce air and water infiltration into cold storage warehouses. The reduced infiltration is because the anterooms are kept at intermediate temperatures (often 10–12 °C), which helps to prevent heat intrusion into cool rooms and also prevents condensation.

3.5. Monitoring, Maintenance, and Operational Practices

The final issues identified by the interviews as important to improving the sustainability and efficiency of cold storage warehouses were monitoring, maintenance, and operational practices. The practices included regular monitoring of the temperature within the temperature-regulated areas of the warehouse, which can give early warning of flaws. Temperature monitoring could be accomplished using sensors and alarms placed in appropriate locations. For example, a small leakage of CO_2 refrigerant could affect the cooling power and overload other components. Hence, the use of CO_2 sensors around the storage area is desired, typically placed towards the ground because CO_2 is heavier than air.

A good monitoring framework will identify many potential maintenance issues, but only if these are acted upon will the outcomes result in improved overall warehouse efficiency. However, even with adequate monitoring and rapid responses to detected problems, ongoing maintenance checks were also recommended by the interviewees. These checks typically vary based on their frequency, ranging from daily to annual checks, depending on the types of checks being performed. For example, certain checks should be performed daily, such as checks of the compressors (for oil leakage), evaporators (for ice formation), and other components relative to the type of refrigeration and temperature requirements of the cold room. Meanwhile, an example of an annual maintenance practice would be the chemical cleaning of a heat exchanger. Thermal scanning checks can be a useful method to diagnose issues with the facility, while site checks for ice and wet spots could also identify issues.

In contrast to monitoring and maintenance issues, operational practices are those behaviors that occur in the warehouse by the staff that can impact the efficiency and sustainability of a cold storage warehouse. Many of these were identified by the interviewees, and these are summarized in Table 5. All of the issues identified in Table 5 have relatively simple fixes but require a high level of awareness and training, and these issues can reemerge if staff and management are not vigilant in ensuring that operations are as efficient as possible.

Note that the tensions that arise between the characteristics of the building (orientation, height, and surface area) and the feasibility of rooftop PV can be somewhat resolved for new buildings by the building being tall and large. That is, a tall building that is large enough to have sufficient surface area for PV resolves that tension. Existing buildings that do not have an optimized surface area to volume ratio and/or orientation can still implement PV if desired and can then rely on other practices (e.g., painted bright colors, effective insulation) to lessen any decrements in possible sustainability.

Table 5. Key examples of operational practices and improvements.

Defect/ Inefficiency	Explanation	Operational Improvements
Leaving machinery and plant idling when not in use	Idling machinery and plant generate heat and wastes fuel.	Raise awareness of plant operators, generate a culture of responsibility
Lack of routine checks and maintenance	Prevention methods are cost- and energy-efficient ways of stopping failures.	Having routine checks and fail-safe sensors allows companies to monitor and prevent critical defects prior to failure, but it needs to be embedded in the culture of the workplace
Inefficient refrigeration components (e.g., poor sequencing of compressors)	Components of the refrigeration system may be overworked or underworked (variable-speed drives).	Automation and frequent monitoring of the refrigeration system ensures the most efficient operation
Overuse of defrosting evaporators to reduce ice build-up	Ice buildup makes refrigeration systems function improperly.	Prevent ice buildup by minimizing air infiltration (condensation) and optimizing compressor usage by having sensors and timers
High infiltration and lack of door protection	Intermittent infiltration, often caused by heavy traffic and frequent door openings, which can account for more than 50% of the total heat load [60].	Mitigating heat losses can reduce the energy needed to cool the space
Inefficient storage practices	Unneeded movement of pallets to reach other items	Automated racking and/or software management tools with updated data
Cooling losses in logistics and freight (products brought in above temperature)	Higher product temperatures when brought into the warehouse cause strain on the refrigeration system and also cause condensation, which can lead to other problems	Improved cold chain logistics (communication with truck drivers and companies). Quick product movement out of the loading bay (the product is not being left there)
Control stetting adjustments	Set points are prone to change (justifiable or not), where the adjustment may be forgotten and/or not changed back	Regularly check settings and restore control settings. Have communication/automation measures

4. Discussion

This study found many practices and technologies that can be implemented to improve the sustainability of refrigerated warehouses. The resulting management innovations were practices and processes (per [43]) organized to reflect the need to use those innovations to improve the sustainability of cold storage warehouses in Australia.

The sustainability innovations can be stratified into a hierarchy of practices and technologies, presented in Figure 3, that distinguish between the practices that are essential and those that are best, applying the considerations raised in Rodwell et al. [47] and Vedder [49]. Practices and technologies in the yellow segment of Figure 2 are those deemed essential for all refrigerated warehouses. In parallel, findings for logistics centers suggest that for those facilities with less automation (such as those at the bottom of the pyramid in Figure 2), energy consumption is driven by the characteristics of the building [25]. Most of the practices and technologies in this segment are possible to retrofit; however, a few should be considered during the design stage of the warehouse, such as building orientation, anterooms, and glycol floor heating.

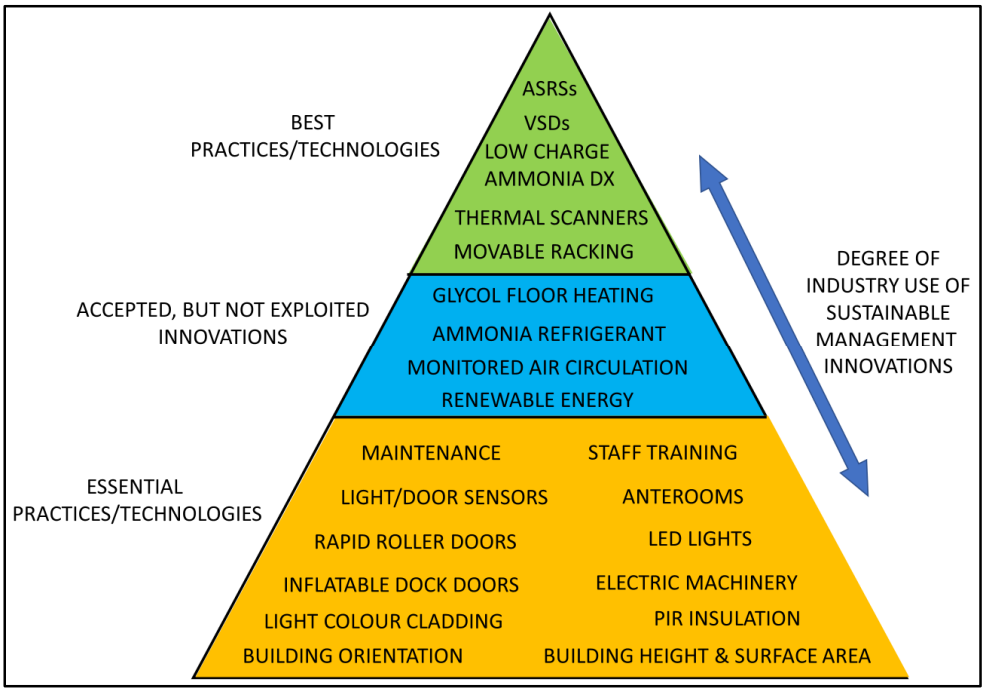


Figure 3. Hierarchy of practices and technologies for cold storage warehouses in Australia.

The practices and technologies in the blue segment represent those that can be retrofitted to further improve energy efficiency and reduce emissions. These practices and technologies are often not perceived as essential. Lastly, the practices and technologies in the green segment are considered best practices. Refrigerated warehouses implementing innovations new to their organization, working from the bottom up to the next most sophisticated level of practices and technologies, will enhance their sustainability.

The text below discusses the nature and impact of the practices and technologies, organized within the categories in Figure 2, then touches on some possible practices that need further evaluation and some general observations about the need to continue making changes based on the Montreal Protocol and its amendments. The discussion of results works from the essential practices and technology, moving upward through the hierarchy.

4.1. Essential Practices and Technologies

In broad terms, the issues most directly associated with managing the energy efficiency of cold storage warehouses can be categorized into three primary areas: design and installation, maintenance, and operational practices. In terms of design and installation, thoughtful

and efficient designs should be implemented, as well as careful installation of components to avoid future defects and flaws. With newly constructed warehouses, the building orientation can be optimized. Ideally, and in best practice, the building should be positioned to minimize exposure to direct sunlight and prevailing winds, thereby decreasing cooling needs [61].

Retrofitting existing warehouses with new and improved technology is quite often a viable option to achieve higher energy efficiency. Retrofits could range from basic operational and maintenance enhancements, such as external painting (lighter colors repel more heat), to repositioning plant and equipment for more efficient material flows. Additionally, companies can either replace individual components or upgrade entire systems. For example, air strip curtains can be upgraded to rapid roller doors to minimize heat infiltration during operations, or sensor-controlled LED lights could replace other lighting alternatives with higher heat loads. Although these solutions may have high upfront costs, the payback periods are relatively short due to the amount of savings arising from these minor improvements [26].

Effective maintenance is essential for the optimal operation of every component within a cold storage warehouse. Routine maintenance practices are more effective than reactive maintenance.

The energy consumption and overall sustainability of cold storage warehouses are heavily reliant on quality insulation practices and technologies. The benefits provided by PIR sandwich panels for wall insulation go beyond mere thermal resistance and were strongly recommended by the experts.

The issues that floor insulation must face differ from those of the walls and roofs. Unlike walls and roofs, floors face consistent ground temperatures that might be warmer than what is required internally [34]. Moreover, the issues of ground moisture and potential frost heave pose a real threat to the structural integrity of the concrete foundation slab on which the warehouse resides [33]. A delineation arising from the results was that chilled storage rooms were not required to have insulated flooring, but insulated flooring is essential in frozen storage areas. The most important way to prevent frost heave is through the use of underfloor heating, particularly glycol.

Managing air and water infiltration is important for cold storage warehouses and can be addressed by focusing on high-quality doors such as RRDs for cold storage entrances and the appropriate use of anterooms.

Typical roller doors were adequate for external entrances such as dock doors, but the challenges associated with docking bays [58] may be addressed by aligning the floor level of the unloading bay with the bed of the transportation trucks, as well as the strategic placement of frequently accessed doors, considering their proximity to delivery trucks and easy access routes for forklifts, which can further reduce the open-door time duration [59]. Finally, the use of inflatable seals can maximize protection against infiltration of air and moisture at docking doors.

For anterooms, a further improvement is to integrate desiccant systems in some anterooms to actively reduce the air's moisture content [36]. Even well-designed anterooms can face challenges, especially with respect to the potential lack of discipline of employees using anterooms in practice. For example, some employees may view anterooms as a nuisance and may keep anteroom doors permanently open, completely diminishing the value of anterooms [37]. Therefore, training plays a crucial role in communicating the importance of the anterooms to the proper operation of the warehouse. Warehouse owners and managers can also use automated tools, such as traffic lights or indicators, that can guide personnel to ensure that only one door is operational at any given moment [37].

The above are examples of basic, essential practices for enhancing the sustainability of cold storage warehouses. The next set of practices and technologies that this research surfaced are accepted by experts as being helpful in improving sustainability but have not been as widely implemented or exploited as they perhaps should be.

4.2. Accepted but Not Exploited Innovations

Perhaps the next key step forward in sustainability improvements for cold storage warehouses would be for them to begin using accepted innovations that are not widely exploited. Using ammonia as a refrigerant is a key example of a well-proven innovation that should be more widely used. Perhaps one reason why cold storage warehouses may be continuing to use HFCs, in the absence of regulatory forcing, is that some refrigeration systems using HFCs cannot be easily retrofitted with ammonia because ammonia is incompatible with some materials, such as copper, commonly used in HFC lines [62]. Such barriers to implementation may contribute to owners hesitating to update technology, leaving some warehouses to fall behind in an ever-changing industry.

For those warehouses that do use ammonia, another issue of concern is which system they use. The findings of this study are consistent with other studies that suggest low-charge ammonia DX systems are more efficient than pumped recirculated liquid overfeed systems [63]. However, the uptake of low-charge ammonia DX systems is slow, and liquid overfeed systems are still predominantly used for industrial-scale applications. The slow uptake is unusual since low-charge ammonia DX systems are superior in nearly all aspects to recirculated liquid overfeed systems outside of the upfront cost. Thus, it appears that upfront capital costs, with less consideration of ongoing costs and sustainability, are the primary obstacle to the slow uptake of low-charge ammonia DX systems.

A further reason for the slow uptake of low-charge ammonia systems may also be a lack of knowledge surrounding the higher energy efficiency of low-charge ammonia DX systems. That knowledge gap indicates that there is not enough exposure to or acceptance of new industry technology trends.

In terms of accepted but not exploited technologies such as PV systems, two particular circumstances may explain some of the hesitancy for the take-up of solar systems—the potentially inadequate structural supports of existing warehouses and situations where the cold storage company leases the warehouse from a third party. In circumstances where the cold storage company is renting a warehouse, there are few incentives for the warehouse owner to install solar panels because they are not responsible for ongoing energy costs. However, there are several ways in which warehouse owners who are not cold storage operators could benefit from the addition of solar panels to their roofs. First, they could invest in solar panels and sell the energy to their tenants. Second, they could enter PPAs (power purchase agreements) with third-party solar developers for lower energy costs and minimal risk. Finally, they could simply lease rooftop space to the warehouse operators for another form of warehouse revenue.

4.3. Best Practices

Many of the best practices and technologies were to do with control and automation, usually after the warehouse has implemented many of the practices and technologies that are lower in the hierarchy. The sustainability best practices for cold storage warehouses included advanced automation such as movable racking, with ASRSs, VSDs, thermal scanners, and low-charge ammonia DX refrigeration systems.

Most warehouses implement the technologies mentioned that help control warehouse processes, such as VSDs, sensors, and PLCs. However, warehouses that do not use these technologies may be unaware of the benefits they can receive, such as the energy savings that can be achieved by implementing variable-speed technology [64]. Perhaps warehouses that do not need strict temperature set points cannot justify the cost of installing VSDs. However, the increased availability of VSDs along with declining costs should see VSDs implemented in more refrigeration systems.

The use of technology such as ASRSs is possible in existing warehouses; however, it is easier to implement in new warehouses, because new warehouses can be designed specifically for the use of ASRSs. In contrast, existing warehouses would require racking to be repositioned and upgraded to cater for ASRSs. Nevertheless, retrofitting existing warehouses with ASRSs would still improve their energy efficiency and productivity.

A possible best practice (per [45]) that may one day be more widely tested and accepted is the use of electricity demand response and load shifting. More testing and evaluation of the best ways to do this practice, perhaps more so for frozen foods in well-insulated buildings with solar panels, needs to be done.

Load shifting is a strategy for managing electricity demand by relocating consumption from high-demand periods to times when demand is lower in such a way that is not detrimental due to the thermal inertia of the product. Warehouses with larger volumes of product may therefore have greater potential returns for applying demand response techniques. Furthermore, lower temperatures (such as those of frozen foods) may present a stronger demand response potential than cooled products, such as fruit and vegetables [65]. Air and products may rise in temperature during a period with a higher set temperature, hence the need for regulation and monitoring during the process in order to not spoil products. However, the risk of food quality and safety degradation means that most industrial frozen food warehouses refuse to use demand response. There may be circumstances where peak load shifting may be more beneficial, such as when the warehouse has solar panels, but ultimately, more studies are needed to further analyze the parameters under which load shifting may be viable and present less of a risk to the stored products.

Further, battery and solar energy storage are becoming commonplace in residential applications but are much rarer in cold storage warehouses, possibly because batteries usually do not meet the substantial energy demands of cold storage warehouses. If more efficient panel technology emerges, battery systems may become viable or useful for cold storage warehouses.

In terms of more general issues in improving the sustainability of cold storage warehouses, it is notable that despite the success of the Montreal Protocol and its amendments, there is still quite a lot more that could be done in managing refrigerant gases. For example, ammonia is recommended above and is increasingly used in refrigerated warehouses because it has great thermodynamic properties as well as zero GWP and ODP. However, there are still some warehouses using synthetic refrigerants such as HFCs with high GWP values, which is a concern when such refrigerants leak, causing substantial global warming impacts [23]. The continued use of less environmentally friendly refrigerants could be a result of governments not being strict enough with phasing out the use of HFCs. For example, Australia is phasing down the use of HFCs by 85 percent by 2036 [66], leaving warehouses to continue to use HFCs in the meantime and also suggesting that some HFCs will still be in use after that date. Since policies are significant drivers for technology change, governments need to make more of an effort to phase out HFC use [55], which could help move more cold storage facilities to use ammonia as a refrigerant.

4.4. Limitations

Perhaps the main limitation of the above findings is that they were based in Australia, a developed country, although international experts from other (developed) countries were also involved. Note, though, that the cold storage warehouse industry in Australia is very fragmented, and many organizations in Australia's cold storage industry could usefully implement the practices and technologies emphasized above. However, the above hierarchy of practices could enable cold storage warehouses by informing them of the practices and technologies to implement at their level and work through to the next higher level and the higher level after that, irrespective of the development of their home economy. The larger discriminator across the practices and technologies is in terms of whether they are being applied for a new site or are to be retrofitted to an existing site.

Furthermore, the practices categorized in this study were the actionable practices and technologies in common that the experts recommended for cold storage warehouses specifically. Recent studies have suggested that if the wider supply chain is considered, then lower-temperature cooling in the cold storage warehouse may lead to sustainability improvements across the cold chain, at least until green electricity-powered trucks become more common [29]. Yet that consideration is not incompatible with the potential of the

improvements suggested in this study. Cold storage warehouse facilities that implement increasingly sophisticated practices from those in Figure 2 will improve their sustainability, and even with the temperature set lower, they could be more sustainable for them and the wider cold chain than they otherwise would be.

5. Conclusions

With the ever-increasing threat of climate change and global warming, we must find new ways to make energy intensive buildings, such as cold storage warehouses (per [23]), that are essential infrastructure for food preservation, more sustainable. Therefore, encouraging searches for practices and technologies that enhance the sustainability of cold storage warehouses is crucial in the battle against climate change and global warming.

The resulting management innovations, consisting of specific practices and processes (per [43]), were delineated in this study to inform cold storage organizations' search for practices that can improve their sustainability. There are many practices and technologies that can be implemented to improve the sustainability of refrigerated warehouses. The practices and technologies were organized into a hierarchy that ranged from essential to best practices, applying the differences in practices and technologies suggested by Rodwell et al. [47] and Vedder [49]. Essential practices and technologies should be implemented by all refrigerated warehouses, whereas best practices may be implemented depending on budget and whether a warehouse is new. Some refrigerated warehouse owners may be unaware or unsure of the benefits obtainable from implementing sustainable practices and technologies. To encourage the use of sustainable practices and technologies, more reporting on successful or unsuccessful applications of practices and technologies needs to be communicated across the industry.

Also note that the practices and technologies in Figure 2 improve the sustainability of cold storage warehouses now, but they are not static and may change over time. That is, the practices and their categorization may change over time, requiring a continuing search for management innovation.

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Review

Definition of Food Consumption, Loss, and Waste

Arkalgud Ramaprasad [1,*] and Shwetmala Kashyap [2]

[1] Department of Information and Decision Sciences, University of Illinois at Chicago, Chicago, IL 60605, USA
[2] WRI India, Bengaluru 560004, Karnataka, India; shwetmala@gmail.com
* Correspondence: prasad@uic.edu; Tel.: +1-312-485-1378

Abstract: The global food system has three recognized challenges: (a) increasing the availability of food for consumption; (b) reducing food loss; and (c) reducing food waste. The increasing demand for food for consumption, the increasing quantity of food loss, and the corresponding increase in food waste are resulting in serious health, aesthetic, social, economic, and environmental problems due to a lack of appropriate planning and management. Despite its importance, there is no clear, concise, and comprehensive definition of food consumption, loss, and waste. Generally, food consumption, food loss, and food waste are dealt with separately. This article presents a logically constructed ontological framework of food consumption, loss, and waste. It gives equal importance to all three aspects of global food management. The systemic ontological framework is general, and the analysis can be applied to any country. The framework deconstructs the combinatorial complexity of the problem and explicates the pathways to manage the consumption, loss, and waste. The ontological framework encapsulates $19 \times 11 \times 7 \times 4 \times 6 = 35{,}112$ possible components of the challenge. A critical analysis based on available data using the framework will help to develop strategies to deal with the problem. It can help us to discover the gaps and to find ways to bridge the gaps. It is a novel way to conceptualize food consumption, loss, and waste together.

Keywords: ontological analysis; systematic; food consumption; food loss; food waste

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1. Introduction

Food loss and waste (FLW) is a complex construct without a "comprehensive and globally applicable" [1] (p. 1) definition. Expressing its complexity clearly, concisely, and comprehensively in natural English (or another language) is a major challenge in defining the construct. The construct's complexity arises from the scale, scope, and semantics of what it denotes. First, food in FLW denotes an array of plant- and animal-based products consumed as food, each with its subcategories. Second, loss and waste denote three sequential steps (consumption is implicit) by which the food is consumed and discharged. Third, food is used by an array of users. Fourth, food serves many purposes for the users. Fifth, and last, FLW is affected by the many stages of food production, storage, processing, and distribution. Thus, FLW is a combinatorial product of the many categories of food, multiple processing steps, different users, their different purposes, and sequential handling stages. There is a very large number of these combinations, each of which is a facet of the construct. Boiteau and Pingali [1] (p. 7) harmonize the definition as follows: "Food loss and waste is a reduction in the quantity or quality of the edible portion of food intended for human consumption when food is redirected to non-food uses or when there is a decrease in the nutritional value, food safety, or other quality aspect from the time food is ready for harvest or slaughter to consumption". Their definition does not express the complexity comprehensively. An ontology using structured natural English (or another language) can express this complexity succinctly. Thus, building on the paper by Boiteau and Pingali [1], we present an ontological definition of food consumption, loss, and waste that addresses the challenge highlighted by the authors.

An ontology is an organization of the terminologies, taxonomies, and narratives of a problem that can be conceptualized as a scientific theory of the problem [2–6]. As a scientific theory, it can be used to describe, explain, predict, and control [7] FLW through feedback and learning [8,9] systemically as part of a broader ecosystem and systematically by exploring the innumerable pathways within it. The authors have used ontologies to study solid waste management [10], bio-medical waste management [11], air pollution management [12], and similar topics. In this study, we (a) present an ontology of food consumption, loss, and waste (the addition of consumption is necessary to make the construct logically complete, although we shall continue to use the common FLW acronym); (b) demonstrate how it encapsulates the present definitions of FLW; (c) discuss how it extends the present definitions to be "comprehensive and globally applicable" [1] (p. 1); and (d) delineate its implications for research on, policies for, and the practice of FLW.

2. Materials and Methods—Ontology of Food Consumption, Loss, and Waste

We approach the problem of unifying the definition of FLW top-down instead of bottom-up, as Boiteau and Pingali [1] have sought to do. We logically deconstruct FLW as

FLW = Stage of food chain + Food type + CLW (Consumption, Loss, Waste) of food + User of food + Objective of food.

We take a systemic view of each subconstruct of FLW in the text equation. Thus, the proposed ontology of food consumption, loss, and waste (Figure 1) is an organization of 60 key words/phrases that define the FLW construct. These are terms selected based on field knowledge and research publications [13,14]. It is a word picture of FLW. The words/phrases are grouped into five columns—each represents a dimension of the problem. They are as follows: (a) Stage—the stages from production to utilization of food; (b) Food—the types of food; (c) CLW (consumption, loss, and waste)—the steps from consumption to waste of food by a user; (d) User—the primary users of food; and (e) Objective—the purpose of food consumption by the user. The words/phrases in each dimension constitute a taxonomy of the subconstruct denoted by that dimension. The elements in each taxonomy are reasonably mutually exclusive and sufficiently exhaustive. The dimensions are ordered left to right with adjacent words/phrases to connect them. Concatenating a word/phrase each from across the five dimensions with the adjacent connectors forms a natural English sentence, as illustrated by the three sentences below the ontology. Each sentence is semantically meaningful (although a little awkward grammatically), and the ontology can generate a very large number of them. The complete set of sentences so generated constitutes the definition of FLW.

Next, we explain the dimensions denoting each subconstruct in the following order: Objective, User, Food, CLW, and Stage. While this is not sequentially right to left, or left to right in the figure, it helps articulate the logic better. We conclude the section with a discussion of pathways to managing FLW that can be generated from the ontology.

2.1. Objective

Food is valued for the energy, the macro-nutrients, micro-nutrients, and for medication purposes [15–19]. It is also valued for the additives and excipients that contain, preserve, deliver, and enhance the first four values. Additives and excipients play an important role in the FLW ecosystem. Last, the residue from one user is valued for the value it may provide for another user (Figure 1—Objective).

FLW is predominantly focused on the first three (energy, macro-nutrition, and micro-nutrition) and residue; it is less focused on medication, and rarely on additives/excipients in as much as they affect the first three. The priority is contextual. In an energy-starved population, minimizing energy loss and waste will be important. In an energy-adequate population, optimizing macro- and micro-nutrition will be important. For all populations, especially those dependent on traditional and indigenous medicine, after assuring energy and nutritional adequacy, preserving the medicinal value will be important. The value of

additives/excipients may be based on explicit knowledge of their capacity to deliver the first four, or on tacit knowledge of historical, cultural, and local practices. The value of residue from a user will depend on the knowledge of its potential for use by another user.

Stage	[of]	**Food**	[for food]	**CLW**	[by/for]	**User**	[for optimal]	**Objective**	[value]
Production		Plant-based		Consumption		People		Energy	
Crop farmer		Grains		Use		Animals		Macro-nutrition	
Livestock farmer		Vegetables		Reduction		Plants		Micro-nutrition	
Fisherman		Fruits		Reuse		Environment		Medication	
Handling		Residue		Loss				Additive/Excipient	
Slaughterhouse		Animal-based		Recovery				Residue	
Transportation		Meat/Poultry		Repurposing					
Logistics		Fish/Seafood		Waste					
Storage		Dairy		Active					
Government		Residue		Inert					
Private		Physical/Chemical							
Processing		Additives							
Local		Preservatives							
Remote		Nutraceuticals							
Packaging									
Distribution									
Wholesale									
Retail									
Formal									
Informal									
Marketing									
Utilization									
Household									
Restaurant									
Hotel									
Institution									

Illustrative pathways:

• Production (crop farmer) of plant-based (grains) for food consumption (use) by people for optimal energy value.

• Handling (logistics) of animal-based (fish/seafood) for food waste (active) by environment for optimal macro-nutrition value.

• Utilization (restaurant) of physical/chemical (preservatives) for food loss (repurposing) by plants for optimal micro-nutrition value.

Figure 1. Ontology of food consumption, loss, and waste.

The properties of food ingredients that determine the different types of value vary. Some properties are visible (for example, energy, sometimes synonymous with quantity), and many are invisible (for example, macro-nutrients, micro-nutrients, and medication). Some are based on formal, explicit knowledge; many are based on informal, tacit knowledge. Some can be measured easily; many cannot be measured easily. These properties determine the efficacy of feedback and learning to manage FLW.

2.2. User

Food is consumed in the traditional sense by people, animals, and plants [14,15,20–22] (Figure 1—User). While the dominant concern is on food intended for human consumption, the consumption by animals and plants must be considered as an integral part of the FLW ecosystem. Food that is not consumed by anyone reaches the environment, which absorbs it. Conceptualizing the environment as a user may be unusual but would help explicitly address the problems associated with environmental protection and sustainability. The four types of users constitute the ecosystem of FLW. Food that is lost or wasted by people may be consumed by animals and plants; food that is lost or wasted by animals may be consumed by plants; and food that is lost or wasted by all three is necessarily consumed by

the environment. Completing the cycle, what is consumed by the environment may affect the subsequent production of food, its quality and quantity, and thus FLW. The iterative cycle may continue thereby increasing or decreasing FLW.

Each user's objectives are different in terms of consuming food and the consequent loss and waste. The objectives vary widely among and between users. The overall objective of managing FLW would be to optimize the value for all the users and their objectives.

2.3. Food

Food is broadly classified as plant-based and animal-based (Figure 1—Food) [23,24]. Plant-based food includes grains, vegetables, fruits, and the residue from the three. Animal-based food includes meat/poultry, fish/seafood, dairy, and the residue from them. Plant-based food may be fed to animals to produce animal-based food; animal-based food is unlikely to be fed to produce plant-based food. There is a third category of physical/chemical food substances that can significantly affect the consumption, loss, and waste of plant- and animal-based foods. These are additives, preservatives, nutraceuticals, etc. While their loss and waste are unlikely to be a major concern, they can have a significant effect on the loss and waste of plant- and animal-based foods. They can also have long-term effects on the subsequent links in the FLW chain.

The subcategories of the three types of food vary in their value to fulfil the objectives for the different users. Balancing them is central to optimizing the value and managing FLW. They are an integrated part of food production, storage, processing, and distribution cycle, but they are interdependent on each other. The composition of food consumed by the users varies based on their requirements, preferences, practices, and objectives. The composition of FLW varies correspondingly.

2.4. CLW (Consumption, Loss, and Waste)

CLW denotes the three—generally sequential—stages of the transformation of food to waste (Figure 1—CLW). Consumption denotes direct consumption, its reduction to other forms, and its reuse by/for the user [15,19,20,25–28]. Loss follows consumption and denotes processes of recovery and repurposing some of the value of food after consumption by/for the user [14,19,25,29,30]. Waste denotes what is left after consumption and loss—it may be active or inert. The CLW stages may be repeated with different users and objectives for the same food. For example, grains rejected by people may be consumed by animals.

The challenge of managing FLW is to optimize the value to the people, animal, and plant users and minimize the waste, both active and inert, reaching the environment. Realizing this may require multiple iterations with different types of food, users, and objectives.

2.5. Stage

Exogenous to the CLW of different types of food by the users for their value are many stages in handling food where too FLW can occur [31]. These stages are production, handling, storage, processing, distribution, marketing, and utilization (Figure 1—Stage). The stages and their subcategories are listed in the corresponding column of the ontology. How the food is handled at each stage can affect its consumption, loss, and waste. Further, since the stages are sequential, the effects of early stages on FLW can be amplified or attenuated in the subsequent stages through appropriate intervention.

The contribution of each stage to FLW will depend on the type of food, users, and the objectives of consumption. These stages may also be spatially and temporally remote from the ultimate user. Thus, loss and waste may occur without an opportunity for the food to be consumed.

2.6. Pathways

The 60 key words/phrases (excluding the column titles and connectors) in the ontology could be combined into ${}_{60}C_5$ = 5,461,512 (60!/(5! × 55!)) 5-word/phrase unique combinations. From these combinations, the ontology encapsulates 19 × 11 × 7 × 4 × 6 = 35,112

combinations that denote the potential pathways to managing FLW in natural English. It is 0.64% of the total possible combinations. These pathways constitute the definition of FLW.

The illustrative pathways generated from the ontology are (Figure 1—Illustrative pathways) as follows:

- Production (crop farmer) of plant-based (grains) substances for food consumption (use) by people for optimal energy value.
- Managing grains loss and waste at the stage of production of crops by farmers for optimizing the delivery of calorific value to people.
- Handling (logistics) of animal-based (fish/seafood) for food waste (active) by environment for optimal macro-nutrition value.
- Managing the logistics of environmental recycling of biologically active fish/seafood waste.
- Utilization (restaurant) of physical/chemical (preservatives) for food loss (repurposing) by plants for optimal micro-nutrition value.
- Managing the disposal of preservatives in food by restaurants as food to plants.

The large number of pathways encapsulated in the ontology as a small subset of the very large number of possible combinations of the 60 words/phrases demonstrate both the generative and selective power of the ontology. It is like a "Google Map" of the challenge of FLW. It can be used to navigate—with feedback and learning—solutions to the challenge, like with the ubiquitous digital map. It shows the large number of pathways, of which some may be known to be effective, some may be known to be ineffective, and many whose effectiveness is unknown. It is necessary to reinforce the effective pathways, redirect the ineffective ones, and research the unknown ones. In the next section, a comprehensive analysis of the current definitions of FLW is discussed through the lens of this framework.

3. Discussion—Correcting the Lacunae

The ontology defines FLW as a multi-dimensional, multi-step, iterative, dynamic process. Each column in the ontology is a dimension of the process. The steps may be within a dimension or may cut across many dimensions. Similarly, the iterations may be within and across dimensions. In other words, the pathways of FLW may crisscross the dimensions of the ontology and the elements within them. FLW is a process not a state. The present definitions fail to capture the dynamics of such an iteration and the associated complexity.

A major impediment to unifying the definition of FLW is the implicit gap in what the acronym denotes—food loss and waste. Loss and waste have a symbiotic relationship with consumption as they are deeply interconnected. As specified in the ontology, the focus should be on consumption, loss, and waste (CLW). Any definition that considers only loss and waste is necessarily incomplete. The ontology avoids this implicit bias.

Boiteau and Pingali [1], in their review, correctly point to the following lacunae in the definitions of FLW:

- "An abundance of terms with overlapping meanings" (p. 3).
- "Definitions driven by perspectives associated with FLW" (p. 5).
- "Timing and terminology" (p. 5) of measurement of FLW.
- Scope of food in FLW.
- Criterion for utilization of food—by who—to determine FLW.
- Criterion of edibility of food—by who—to determine FLW.
- Type—quantitative and qualitative—of FLW.

It is an excellent list. However, the harmonized definition the authors propose does not resolve the lacunae and help unify the definitions. In the following, we explain how our ontology can provide a unifying definition of FLW that addresses the above issues and is a "comprehensive and globally applicable" [1] (p. 1) definition.

3.1. Parsimonious Terminology

The 60 key words/phrases in the ontology, derived from the common body of knowledge on the subject, are adequate to define FLW. The columns represent distinct dimensions of FLW and are comprehensive. The taxonomies of the dimensions are reasonably mutually exclusive and sufficiently exhaustive. The organization of the ontology is such that (a) a dimension can be added to extend the scope of FLW; (b) each dimension's taxonomy can be extended, if necessary, by adding elements; and (c) the elements of a dimension can be refined by adding sub-elements and coarsened by aggregating elements to change the granularity of the definition. The modularity of the ontology lends itself to such changes without the necessity of reworking the whole definition. Such additions and refinements may add only a few terms, but extend the scope (dimensions), scale (magnification), and size (number of pathways) in the ontology exponentially. The ontology, with parsimonious terminology, can capture the complexity of FLW clearly, concisely, and comprehensively.

Even if the terminology of the ontology is not identical to that in the definitions, one can establish equivalence through synonyms, hypernyms, and hyponyms. Keeping the ontology constant as the framework for integrating the definitions, in line with the top-down approach, would be easier than attempting to integrate and unifying them ground-up.

3.2. Stakeholder Perspectives

The present ontology includes the perspectives of the stakeholders in all the stages from production to utilization, steps from consumption to waste, and users from people to the environment. A stakeholder's perspective can be denoted by a subset of the ontology. Multiple stakeholders' perspectives can be integrated by mapping them onto the ontology. The modularity of the ontology makes such denotation and integration possible. Further, the ontology's scale, scope, and size can be changed (as described earlier) to accommodate and fit any stakeholder's perspective.

Last, the ontology can frame a stakeholder's perspective in the unified context of the universal definition. Such a part–whole framing will highlight the systemic biases in a stakeholder's perspective—what is emphasized, what is not emphasized, and what could be emphasized. Such an analysis will help define the intended consequences of the definition, its unintended consequences, and its potential innovative consequences.

3.3. Timing and Terminology

The timing and terminology issue is that of choosing the segment of the Stage dimension for the definition. Considering the cascading interdependence of the stages, it would be appropriate to include all of them. However, should one want to study Handling in greater depth and detail, the other stages can be hidden. Further, additional subcategories of handling can be added for greater detail, and sub-subcategories can be added for greater depth.

Continuing, the focus can be further narrowed to plant-based foods by hiding other types of foods, and to people's CLW by hiding other users. Thus, the ontology (a) provides an integrated timing framework and (b) permits segmentation of the timing based on a stakeholder's requirements.

3.4. Scope of Food

The denotation of food in the ontology is inclusive and exhaustive. In addition to the plant- and animal-based foods, it also includes physical/chemical ingredients in food. The last category, likely to be present in minute quantities compared to the bulk of what is considered food, can have an oversized influence on FLW and the value the food delivers. Food in the ontology also includes residue from plant- and animal-based foods that could likely be used by a different user in a subsequent iteration [32,33].

By refining the food categories, the ontology highlights the importance of considering the differences in their CLW. These subcategories fulfill different objectives and have different user profiles.

3.5. Utilization of Food

The food may be utilized by people, animals, plants, and the environment. It may be utilized in a household, restaurant, hotel, or an institution. There is an interdependence between the utilization by the four users that is a necessary part of the food ecosystem. Loss or waste for people may be a gain or choice for the animals and plants. Thus, the estimation of FLW utilization will depend upon the boundary chosen. It may include only people, people + animals, people + animals + plants, or people + animals + plants + environment. It is a problem of definition that will also likely affect the temporal boundaries for the determination of FLW. Focusing on a single type of user will have the shortest time horizon, adding more types will expand the time horizon. Thus, if one is focused only on the short-term FLW, one may focus on a single type of user; on the other hand, if the focus is on long-term FLW and ecological sustainability, one must focus on the full spectrum of users.

3.6. Edibility of Food

The edibility of food depends on its user. Food that is inedible to people may be edible to animals; food that is inedible to animals may be edible to plants; and food that is inedible to plants may be "edible" to the environment by default. The propagation along the edibility chain will depend upon the type of food and its subtype. Plant-based food may propagate better than animal-based foods. Ultimately, all waste must necessarily be "edible" to the environment, with potentially desirable and undesirable long-term consequences to the food cycle.

Further, physical/chemical ingredients in the food, both plant-based and animal-based, can affect its edibility to the users and consequently its FLW. These substances may be introduced at one or more of the stages from production to utilization, consumption-reuse, or loss-recovery and loss-repurposing. Thus, edibility may be transformed in significant ways for each type of food as it undergoes iterations among the stages, CLW steps, and the users.

3.7. Type of FLW

The ontology can describe all possible types of FLW qualitatively and exhaustively. It would be difficult to quantify all the qualitative descriptions due to difficulties of measurement, availability of data, quality of data, and similar factors. However, the challenge of quantification must not deter one from addressing a type of FLW.

Quantification can take place at many levels [14,34,35]. At the nominal level, one may simply measure the presence/absence of a type of FLW. At the ordinal level, one may rank order different types of FLW. At the interval level, one may assign subjective regular interval scale values (for example, using a Likert-like scale) to the FLWs with an arbitrary anchor. Last, at the ratio level, one may measure FLW on a scale with an absolute zero and objective, regular interval scale values. Nominal and ordinal level specification can be very relevant despite not appearing to be rigorous. Interval and ratio level specification can be rigorous but, due to challenges of measurement, quality of data, and related issues, may not be very relevant. The ontology specifies all possible types of FLW qualitatively; from them, one can choose the level of measurement suitable in a context.

3.8. Managing the Dynamics of FLW

FLW is a dynamic process and not a static state of a household, organization, locality, city, state, or country. Like on a "Google Map", food traverses many pathways in the ontology in the process of being consumed, lost, and wasted within the boundaries of the entity. Many of these pathways have been discussed above. The pathways are iterative, cutting across many dimensions, and including many elements of a dimension. They are

complex, and navigating them through systematic feedback, learning, and redirection can optimize the value of objectives of user food consumption and manage the associated loss and waste. The ontology provides a framework for such feedback, learning, and redirection in research, policies, and practices.

Mapping the state-of-the-research on, -policies for, and -practice of FLW will highlight the gaps in each and the gaps in translation between the three. It will highlight the elements and themes that have been (a) frequently emphasized, (b) infrequently emphasized, and (c) never emphasized. From such a systematic analysis, one can draw conclusions about (a) pathways that have been effective and must be reinforced, (b) pathways that have been ineffective and must be redirected, and (c) pathways that have not been explored and must be researched.

3.9. Differentiation and Integration of FLW

Food CLW patterns can vary significantly by country, region, locality, geography, culture, and other parameters [24,36,37]. In medium- and high-income countries, food is significantly wasted at the consumption stage, whereas in low-income countries, food is lost mostly at the food loss stage [36]. These differences can be mapped within the framework and integrated within it. The patterns may also change over time due to a crisis like COVID-19 [38], type of use [39], the socioeconomic development of society [40,41], and other factors. These changes too can be integrated within the framework. Last, the patterns will be different based on the scale, scope, and size of the object of the study. Instead of one strategy being force-fit for all scales, scopes, and sizes, the framework permits the analysis of the differences and their integration into a coherent system.

To address the problem of FLW from any of the many above points of view, it is not necessary to consider the entire framework. One can define the boundary of a problem in a context by making the relevant elements endogenous and the others exogenous. Thus, to study the problem the point of view of utilizing stakeholders (household, restaurant, hotel, and institution), the earlier stages may be defined as being exogenous to the study. Similarly, for a micro-level study of vegetarian households, animal-based foods would be exogenous, although animals as users would be endogenous for plant-based food residue is often fed to animals.

By the same token, the framework can be used to integrate the research from different points of view, sizes, scopes, and scales. It is this ability that can be used to derive a "Google Map" to address the problem of FLW systemically and systematically.

3.10. Opportunities for Empirical Research

The ontology, as a theory of food consumption, loss, and waste, can be a systemic foundation for systematic empirical research on the subject. It can be used to synthesize the present empirical research on the subject and generate new research. It can be the foundation of descriptive, explanatory, predictive, and experimentally controlled research on the subject. Mapping the extant research, policies, and practices onto the ontology will highlight the bright, light, and blind/blank element/pathways in them. Harnessing the knowledge from the present research and promoting new research to fill the gaps would be the objectives of the empirical research. The following are some of the questions empirical research may address:

- Descriptive research of patterns of CLW by people in different parts of a country and different countries.
- Explanatory research of the flow of plant-based food cycles among the people, animals, plants, and the environment.
- Predictive research of the change in content of free meals for school children on the objectives.
- Experimentally controlled research on the effect of processing of additives and preservatives in food consumed by people on the residue.

- Quantitative measurement and monitoring of CLW in an institution to predict future FLW.
- Field experiments to find ways to reduce food loss and food waste while increasing nutrient food consumption.

3.11. Value Added by the Ontology

We conclude our discussion by highlighting the value added by the ontology to advancing the research, policies, and practices for the management of FLW. It is true that the terms and concepts of the ontology are familiar to experts in the field, and that they have been explored and applied globally by international organizations such as the United Nations, Food and Agriculture Organization, and the European Community. While the institutions' frameworks clearly highlight many of the key issues in managing food loss and waste, they also have very significant biases and blind spots that can affect the strategies for and outcomes of managing FLW. The ontology corrects these shortcomings. We discuss how the ontology can enhance the present body of knowledge and practice of FLW.

It has become a cliché to state that a whole system is greater than the sum of its parts. The ontology encapsulates this principle. It makes the whole visible—like the wise man [*sic*] does in the parable of the blind men and the elephant—and changes the perspective, making it more than the sum of the familiar elements. By organizing the familiar elements systematically and extending them logically, it provides a systemic perspective that illuminates and enhances the traditional perspectives. It formulates the problem more inclusively. Thus, it highlights and corrects the biases and blind spots of the extant frameworks. Instead of re-emphasizing more of the same traditional avenues, it incorporates and extends them to develop novel ones. We shall highlight a few.

The ontology extends the focus from FLW to food consumption, loss, and waste (CLW). The implicit bias in excluding consumption significantly affects the management of loss and waste. Yet, the exclusion persists. If an element is not part of the problem formulation, it will not be part of its solution; consumption must be part of the problem and the solution. CLW by the four types of users (people, animals, plants, and the environment) in the ontology is a zero-sum game for sustainability and must be managed systemically. The simple extension of focus may appear minor, but it can have a dramatic impact on the outcomes. It introduces the pathways of changing loss and waste by changing consumption patterns of use, reduction, and reuse by the different users.

The ontology highlights the necessity of considering all the four types of users for a sustainable ecosystem. People's CLW has been the dominant concern in the scientific literature, policies, and practice. This skews the perspective, for the CLW of animals and plants too are integral to how the CLW chain affects the environment and is affected by it. Further, by denoting the environment as a user, the ontology makes it endogenous to the challenge of managing food CLW and not exogenous to it. The environment is considered a part of the problem and not just of the solutions for sustainability.

The ontology includes both plant-based and animal-based foods and sidesteps the either/or debate about their inclusion/exclusion in some of the frameworks. Systemically, both, with their physical/chemical components, must be managed. The ontology rises above the either/or debate and provides an inclusive perspective and eliminates potential blind spots.

The ontology includes all stages of the supply chain for all types of food for all users. Managing the sequential dependence in the chain is critical to the effective management of food CLW for sustainability. The feedback loops between the stages, from subsequent stages to the prior ones, and the feedforward loops from the prior to the subsequent stages are not explicated in the ontology but can be visualized systematically using it. They play an important role in maintaining the continuity of pathways that are effective, changing the ones that are not effective, and discovering ones that have been unexplored. Instead of studying the food supply chain as a silo, the ontology helps visualize the chain as integral to the system of managing food CLW.

The ontology presents an integrated perspective on the value of food—energy, macro-nutrition, micro-nutrition, medication, additive/excipient, and residue. The value requirements vary by the user, and the value delivered vary by the type of food. Further, the pattern of consumption, loss, and waste of food by the users for obtaining these values vary widely. The ontology provides a framework to manage the pathways to deliver these values optimally.

Thus, the ontology can be used like a "Google Map" to navigate the pathways to optimize the value of food CLW. While many pathways may be familiar, many are not. Feedback and learning using the ontology can aid continuity, change, and discontinuity in the optimal management of CLW. It can help lessen "more of the same" solutions and increase "many of the different" solutions, as illustrated above.

3.12. Research Limitations

The ontology is a structured natural English framework. Its validity is partly determined by the semantics of the words, phrases, and pathways in it and derived from it. Consequently, it is subject to variations based on the syntax and semantics of the language, the users, and the context. The simplicity of the framework allows it to be easily transferred to other contexts, translated into other languages, and applied using the local vernacular; however, care must be exercised to accommodate the differences in the grammar and semantics of the languages and dialects.

A second limitation of the ontology is the granularity of its representation—it matches the granularity of the present discourse on the subject. Yet, to address FLW effectively, one may need to address it at a finer level (for example, different types of grains) or at a coarser level (for example, loss in the aggregate, without considering recovery and repurposing). Changing the granularity will affect the number of pathways combinatorially, and hence the complexity of the challenge. It may become necessary to focus only on a segment of the ontology, and not the whole, at a different level of granularity. For example, one may focus the research only on the utilization stage and not include the other stages.

A third limitation of the ontology is the boundary it defines. The denotations of the dimensions and the elements define the inclusion/exclusion of parameters that affect FLW. For example, the context (country, culture, geography, socioeconomic structure), the scope (block, city, district, state, country, region), and timeframe (short-term, medium-term, long-term) are exogenous to the present ontology. By choice, the ontology focuses tightly on the core logic of FLW. The other dimensions can be added to change the scope, if necessary, with the concomitant increase in complexity and the number of pathways. The scope could also be decreased by eliminating a present dimension (for example, the Objective), but that would diminish the logical validity of the ontology.

These limitations can be overcome easily because of the modularity of the ontology. A dimension can be added or deleted without prejudice to the others, taxonomies can be refined and coarsened, and they can also be extended with new elements and contracted by eliminating redundant ones. Such changes will change the size (the number of dimensions and elements), scope (the type of dimensions and elements), and scale (the granularity of dimensions and elements) of the problem definition and the associated complexity.

4. Conclusions

The paper presents a unified definition of food consumption, loss, and waste as an ontology. The construct's combinatorial complexity cannot be clearly, concisely, and comprehensively expressed in a traditional linear narrative. It requires an ontology. The paper relates the ontology to the other extant definitions of the construct and assesses them systematically to integrate the definition of FLW and address their lacunae. With the increasing demand of sustainable practices for food consumption and reducing the food loss and food waste in the system, it becomes important to understand the system. The framework helps to define the construct to include all three—food consumption, food loss, and food waste. It can help understand the dynamics of the full spectrum of stages, their

impact on consumption, loss, and waste, and the complete knowledge cycle associated with it.

The paper addresses a pressing need of the domain and presents a framework that is integrative and innovative, consonant with the need for solutions with similar characteristics. The novel systemic framework can guide the development of roadmaps for systematic research, policies, and practices to address the challenge. It can help to identify and to rectify the biases and blind spots in the current approaches and to institute a system of feedback and learning to guide the future trajectory of the domain.

The contribution of the ontology of food consumption, loss, and waste is analogous to that of the "wise man" [*sic*] in the parable of the blind men and the elephant. By making the whole visible, it can help integrate the many fragmented, often conflicting, and complementary definitions. It can help advance the agenda for research, policies, and practices on the subject through collaboration and cooperation. It can help formalize knowledge in the three domains, transfer knowledge between the subdomains, and translate knowledge between them to achieve the Sustainable Development Goal target 12.3 [1], food security [42], and nutrition security [43].

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A User-Friendly and Sustainable Toilet Based on Vermicomposting

Fernando Alonso-Marroquin [1,*], Ghulam Qadir [1,*], Jad Nazha [1], Vanessa Pino [2] and Arianna Brambilla [3]

[1] School of Civil Engineering, The University of Sydney, Camperdown, NSW 2050, Australia
[2] School of Life and Environmental Sciences, The University of Sydney, Camperdown, NSW 2050, Australia; vanessa.pino@sydney.edu.au
[3] School of Architecture, Design, and Planning, The University of Sydney, Camperdown, NSW 2050, Australia; arianna.brambilla@sydney.edu.au
* Correspondence: fernando.alonso@sydney.edu.au (F.A.-M.); ghulam.qadir@sydney.edu.au (G.Q.)

Abstract: Environmental awareness has sparked increasing interest in changing the way humans interact with their environment. This awareness includes the change in paradigm of considering human manure (humanure) not as a waste but as a valuable bioproduct instead. In this regard, composting is an age-old technique for nutrient recovery that has gained renewed interest, as it may be a sanitary and financially viable solution to closing the loop of human–nature interactions. This work investigates environmental solutions for toilet systems that are user-friendly and sustainable based on systems that filter nutrients via vermicomposting. The methodology is based on (1) reviewing several surveys across different continents to select the most appropriate interface of a targeted society, and (2) investigating the microbial dynamics of vermicomposting. The microbial activity was compared with the activity of the aerobic composting systems by measuring soil temperature, soil composition, decomposition rate, stabilization factor, and biological diversity. The microbial decomposition process in vermicomposting was faster due to the presence of earthworms, but the increase in temperature and volatile ammonia led to the earthworms burrowing into the soil. Overall, the flush toilet is still the most socially accepted toilet interface, and the connection of vermicomposting to this toilet interface poses challenges in managing high ammonia content and maintaining healthy conditions for the earthworm population.

Keywords: waste management; biophilia; vermicomposting; UN goals; climate change

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1. Introduction

Human waste management systems have made substantial advancements over time. Still, globally, 3.6 billion people lack access to safely managed sanitation services [1]. But in terms of percentage, 90–100% of the population in developed countries have access to safe sanitation compared with 50–70% in under-developed countries [2]. Also, the unhygienic practice of open defecation is very rare (1%) in developed countries [3] but due to a lack of toilet facilities, this percentage is around 15–20% in under-developed countries as the use of unimproved pit latrines and open shared latrines is quite common, contributing to this high percentage [4]. Many countries have well-established systems to control sewerage that have played a vital role in the minimization of contamination and disease spreading. Nonetheless, in cases where sewerage systems are accessible, the presence of such infrastructure still encompasses serious environmental and socio-economic implications. For example, the accumulation of nutrients in water resources (eutrophication) [5], the destruction of coral reefs [6], and greenhouse gas emissions by sewerage systems and treatment plants [7] provoke substantial costs and environmental threats. The composting of waste into nutrient-rich fertilizer represents a biophilic approach that may support a reduction in such risks. This process can be classified into two prevalent categories: aerobic composting (AC), which utilizes bacteria for decomposition, and vermicomposting (VC), which engages

the use of both bacteria and earthworms for decomposition. Another method is anaerobic composting, which occurs in an airtight closed container and makes use of microorganisms that do not require oxygen to break down waste, generating methane (CH_4). This methane is a useful source of energy; however, it is powerful greenhouse gas when released into the atmosphere [8].

AC has gained a significant level of development and establishment, as demonstrated by the presence of commercial aerobic composting toilets and the regulations governing their usage. On the contrary, VC toilets represent a novel technology that has been garnering significant attention in the scientific community in recent times. But overall, there are no specific regulations on composting toilets (AC or VC), even in developing countries, e.g., in the US, there is a general lack of detailed guidelines [9]. As per regulations, composting toilets are permitted on site where soil conditions are unsuitable for onsite sewage treatment or water under pressure is not available from the municipality and in flood-prone areas [8].

Different research studies [10,11] have highlighted the advantages of VC over AC in various aspects such as sanitation, compost quality, and operational results. VC surfaced as a highly esteemed fertilizer in agriculture, asserting a premium price compared with conventional compost [12]. Contemporary research in the field of VC toilets has primarily focused on process optimization. For instance, a comparative study [13] was conducted to gauge the effectiveness of various filter media used in vermifilter toilets, ultimately concluding that river bed material yielded the most favorable results. Another study [14] focused on comparing different worm bedding materials, finally identifying coir and woodchips as the top-performing options. In recent times, a research study [15] conducted a comparison of various VC hydraulic loading rates and filter media compositions, intending to determine the most affirmative loading rates and layouts.

Although extensive research has been devoted to optimizing specific aspects of the vermicompost toilet, a comprehensive design that adopts these recommendations into a user-friendly and sustainable solution is yet to be established. There is also limited information available regarding the social acceptability and financial viability of such a toilet, as both are crucial factors in achieving the broader objective of utilizing composting designs to direct waste management challenges. Enhancing the understanding of VC toilets and promoting their large-scale adoption requires conducting an extensive analysis of vermicomposting's effectiveness in contrast to aerobic composting. Furthermore, improving the VC design and gaining insights into the solution's social acceptability and financial viability are crucial steps to advance the VC toilets' potential.

In this regard, this research proposes an innovative and optimized composting, microflush toilet design. This paper first discusses the composting reactor mechanism and the use of toilet user interfaces. This is followed by a review of the social perception of eco toilets across different continents by analyzing survey results. Based on that, a design for a vermicompost chamber is proposed, and a composting experiment is set-up. An ecofriendly aspect is added to the design by connecting the composting systems to native plants that re-absorb the nutrients and close the cycle of nutrient recovery with minimal human intervention. The experiment has three composting systems, which include soil compost, compost with manure, and earthworms with manure compost. A comparison between the systems is then drawn based on the analysis of the compost temperature, physicochemical properties, and micro fauna analysis (tea bag index tests and DNA sequencing). This gave a blueprint of the composting effect on the soil. In the end, suggestions are given for the best toilet user interface.

2. Composting Reactor Systems

Aerobic composting (AC) takes place in adequately ventilated environments, where oxygen-utilizing microorganisms disintegrate and decay organic matter. In this composting process, aerobic microorganisms, such as bacteria, actinomycetes, and fungi, facilitate the oxidation of organic materials, resulting in the production of carbon dioxide (CO_2), ammonia (NH_3), water (H_2O), and volatile compounds [8]. AC has different stages: mesophilic,

thermophilic, and curing stages. Mesophilic composting takes place within a temperature range of 20–40 °C and generally lasts for a few days. In this stage, the mesophilic bacteria commence the decomposition of organic matter and generate substantial heat, which triggers the successive phase of thermophilic composting. Thermophilic composting takes place over several months. This stage is characterized by the dominance of thermophilic bacteria that thrive in higher temperatures, ranging between 45 and 65 °C. The bacteria in this stage metabolize proteins, fats, and carbohydrates, while the heat generated during this stage helps eliminate pathogens. Eventually, as the depletion of the energy sources occurs, the temperature steadily decreases, and this leads to the final curing phase where mesophilic organisms once again become dominant and decompose any remaining organic material. Efficient aerobic composting requires specific conditions to be met, e.g., an oxygen concentration of 15–20%, a moisture content between 50 and 65%, a temperature ranging from 50 to 65 °C, a carbon-to-nitrogen ratio of 25–30, pH levels between 6.7 and 9, and a porosity of 35–50% [8]. For optimal composting, it is essential to control these factors through measures such as employing ventilation fans, regular mixing, water sprinklers and drainage systems, heaters, and insulation, as well as an assortment of high-carbon materials in the form of sawdust, shredded paper, coffee grounds, straw, etc.

Vermicomposting (VC) employs earthworms and microorganisms to break down organic matter and generate nutrient-rich vermicompost, or worm compost. This process consists of two primary stages: the active stage, facilitated by earthworm digestion, and the maturation stage, driven by mesophilic bacteria and fungi. In the former, the earthworm's digestive system utilizes enzymes, intestinal mucus, and natural antibiotics to eliminate pathogens and foster a diverse and beneficial microbial community that enhances plant growth [16]. After traversing the earthworm's digestive tract, the organic matter is excreted as "casts" surrounded by microorganisms, enzymes, and fermenting substances. During the successive maturation phase, bacteria and fungi promptly act upon the partially digested casts, transforming them into mature vermicompost. Unlike AC, this entire process takes place within the mesophilic temperature range (15–28 °C) for optimal performance. Within 4–8 weeks, this process yields valuable vermicompost that enriches soil fertility, promotes plant growth, eliminates harmful pathogens, and aids in disease management [16]. For developing an environment for vermicomposting to grow and to create an optimal ecosystem, specific conditions distinct from aerobic composting are compulsory. These conditions include maintaining a higher moisture content of 60–75%, lower temperatures (preferably around 25 °C, but with survival possible within 0–35 °C), a reduced carbon to nitrogen ratio of 25:1, lower pH levels of 6.5–8, and moderate porosity to facilitate worm burrowing (35–50%) [17]. Through various means, these conditions can be achieved, e.g., incorporating high-carbon materials, utilizing ventilation fans, providing insulation, implementing water sprinklers, and establishing effective drainage systems.

The construction of a vermicomposting reactor requires the implementation of a worm filter, also known as a VC filter. This biological filtration system engages earthworms to break down organic matter and filter the resulting liquid as a by-product known as vermicast [18]. Within the VC, the vermicast passes through layers of organic materials, such as peat moss, coconut coir, or compost, serving as a substrate for the earthworm bed. The earthworms maintain the aeration of the compost through the tunneling system they create, and they increase the compost temperature through their metabolism. The worms consume the organic matter and convert it into worm cast (solid phase) and worm tea (liquid phase). Driven by gravity, the worm tea, along with the diluted cast, undergoes filtration through a series of granular layers with varying grading. The final liquid holds considerable value as a nutrient-rich soil amendment, suitable for gardening or agriculture usage [19].

3. User Interfaces

The "Toilet interface" envelopes different interactive elements that ease individuals to engage with a toilet, notably in accommodating diverse genders, ages, and abilities. An

optimal interface encompasses a range of components and features that ensure maximum levels of hygiene, comfort, and satisfaction during toilet use. Therefore, it is important to understand how each toilet interface adapts to the idiosyncrasies and customs of a particular social group.

In ancient civilizations, the toilet systems consisted of holes or pits in the ground. A remarkable example is the communal spaces of ancient Rome [20], reflecting a collective acceptance of bodily functions as natural and integral parts of life. However, as societies evolved and notions of privacy and modesty emerged, toilets became enclosed and private spaces, often associated with shame or embarrassment. The flush toilet that we know today has roots back to the 16th century as Sir John Harington invented the first flush toilet [21]. This was followed by the tank-based flush toilets in the mid-19th century first presented as patent by Alexander Cummings, who had an idea of using a separate water tank for flushing [22]. By the mid-1980s the dual-flush toilets were in use [23]. In the late 20th century, sensor activated toilet technology was introduced and it gained progressive popularity [24]. In recent years, bidet toilets and smart toilets are mostly driven by Japanese innovations, but they are still not widely used [25].

There are several types of toilets. Therefore, a characterization was proposed based on (1) the position adopted by the user (standing [26], squatting [27], sitting [28], etc.) and (2) the evacuation method of humanure from the user interface was also taken into consideration, including options like dry/flush urine-diverting toilets, dry toilets, and flush toilets.

The three most common toilet positions are standing, squatting, and sitting. Standing is commonly used for male urination [26]. Squatting is an organic posture that helps to build the pressure required for easy evacuation [27]. Sitting is a comfortable position that requires physical contact with the toilet, which is widely adopted in Western societies [28]. In the classification of toilets that uses the method of evacuation of the humanure, there are three general methods, dry toilets, urine-diverted toilets, and flush toilets. The "dry toilet", also called the latrine, shown in Figure 1a, operates without flush water, and it is placed over pits. The humanure and the cleansing material are evacuated by gravity. Latrines do not have a water seal to stop odors. These toilets are designed usually for sitting rather than squatting. They allow the waste to decompose through natural processes. Typically, the waste is deposited into a chamber or container where it undergoes composting.

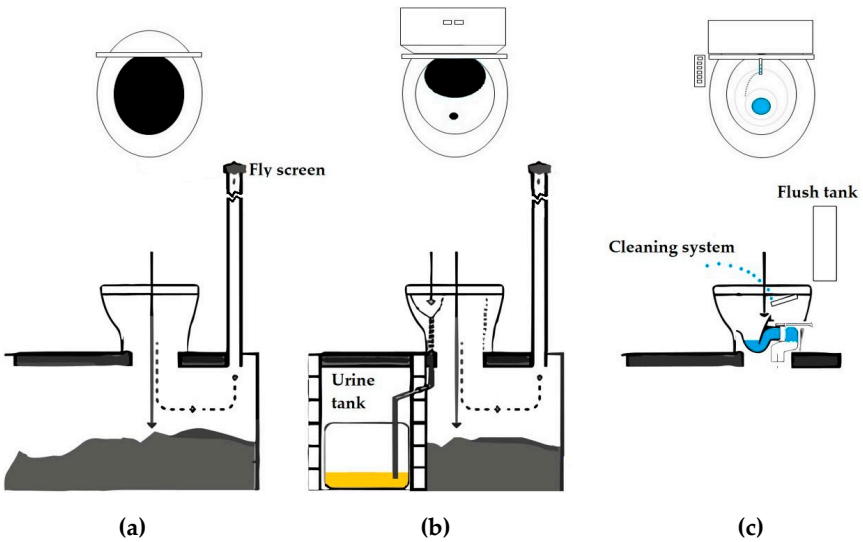


Figure 1. Top and cross-section view of typical toilet user interfaces, showing the place of urine and stool through arrows pointing downward: (**a**) Dry toilet latrine. The fly screen shown is used to keep insects, dirt, leaves, and debris away from the composting chamber. (**b**) Waterless urine-diverter toilet with a separate chamber for urine collection. (**c**) Flush toilet–bidet with a combination of micro flush technologies and a water jet cleansing system.

The urine-diverter toilet is shown in Figure 1b. The interface collects urine in the front of the toilet, and solids are collected in the back, using separate compartments. By separating humanure at the source, urine diverters enable greater nutrient recycling, offering the possibility to convert urine into a valuable fertilizer. This type of toilet can accommodate both sitting and squatting positions and also both dry and flush models. There is flexibility for catering to user preferences in the design. But due to social acceptance and high labor costs, there are certain limitations in the use of urine diverters.

Urine contains a relatively high concentration of nutrients, including 80% nitrogen, 50% potassium, and 50% phosphorus [29]. The urine-based fertilization can be performed through two low-cost methods. The first method for nutrient recovery is to dry the urine and keep the urea $(NH_2)_2CO$ as a solid material to be used as fertilizer [30]. In the second method, urine is collected and mixed with water creating a diluted solution that is directly applied to the soil [31]. The natural bacteria present in the soil convert the urea into ammonia (NH_3) and then into nitrates ($NO_3{}^-$) that are assimilated by plants to build amino acids. These are essential nutrients in the food chain. Potassium and phosphorous are essential elements in the food chain that, unlike nitrogen, are not present in the atmosphere. Although urine-diverting toilets are available for use, societal acceptance may not be immediate. It is prone to misuse and clogging. The capital and operating costs are high. A survey study of 17,499 households in South Africa revealed low satisfaction with such facilities and a perceived odor in the toilets, leading users to prefer flush toilets [32].

The centerpiece of today's modern user interface is the flush toilet. The first patent was granted to Alexander Cumming in 1977 and included the s-shaped pipe below the bowl that seals odor from entering the bathroom. The main drawback of the flush toilet is that it uses large amounts of water, very often drinkable water, for the flush operation. However, modern toilets have created new technologies to reduce the water used during the flush, such as double flush buttons, and micro-flush systems that combine non-stick technologies with tornado-like flush modes for efficient evacuation. Thanks to these technologies, the amount of water required to flush has been progressively reduced from 20 litres to 3.5 litres. Many companies in Japan, e.g., Toto, have established a reputation for producing high-quality toilets that prioritize performance, comfort, and sustainability [33]. The TOTO electronic toilet operates as a Smart Toilet, working with an integrated water-cleansing system for superior and comfortable personal hygiene [34]. The Toto-toilet is shown in Figure 1c.

4. Social Perception of Toilets

Toilets are fundamental facilities for every human being, yet the acceptance of society towards the new toilet system is influenced by cultural attitudes and social perceptions towards hygiene, privacy, and social norms. The choice of a suitable combination of user interface and the composting method for a sustainable toilet should consider different factors of the targeted community, such as hygiene practices, economic priorities, connectivity with the environment, and gender-related preferences. This paper focus on determining the acceptable levels of people regarding composting systems, or no-mix (urine-diverting) technologies, across various locations worldwide: the United States [35], Europe [36], Philippines [37], and Australia [38]. To achieve this, survey reports from the literature were analyzed.

Positive acceptance and a willingness to adopt sustainable technologies, e.g., eco-toilets (ET) and urine-diverting toilets (UDT), has been reported in four different continents. In these surveys, the ET was presented as a system that uses a small amount of water or no water and recovers nutrients from human waste, and the UDT as a system that separates urine and solid waste during the toilet-use process. Two locations in the US have been surveyed: Cape Cod Island [35] and Hawaii [35]. In Cape Cod Island [35], only 42% of the participants had positive attitudes about septic systems and many were willing to adopt eco-toilets. Most respondents would be completely willing to use an ET in a friend's home (63%), and many would be completely willing to stay at a hotel or

other short-term lodging with an ET installed (46%). The percentage of respondents who agree that the risks of using an ET are acceptable to obtain the benefits was much larger than the percentage who reported complete willingness to install eco-toilets in their own homes. This difference suggests that more participants would accept the risk-versus-benefit tradeoffs than the group that may be eco-toilet advocates. In Hawaii, 84% would allow to have a UD toilet installed in their home and 65% would pay about 50 USD to have a UDT in their home [35]. A comprehensive survey in Europe across seven different countries revealed that participants considered UD toilets to be the same or better than conventional toilets in terms of hygiene (85%), smell (77%), comfort (86%), flushing (56%), and cleaning (52%) [36]. In the Philippines, the main factors to be considered by all respondents for installing an ET at their home/community were (1) opportunities for saving water (47%), a shouldered cost of the installation of an ET, and the reuse of the nutrients from humanure (22%) [37]. In Australia, 30% of the respondents were positive towards the UDT but only 15% had a positive attitude towards dry ET [38]. Overall, the survey reports across the mentioned locations revealed that most of the users have positive acceptance and a willingness to adopt eco-toilets and urine-diverting toilets. But still, there is a need for further developments and public education to address the risk and benefits related to these types of toilets.

The surveys also reported on the attitude of the community towards the recovery of nutrients from humanure. In Hawaii, 82% of the respondents conveyed that human waste can be safely recycled instead of being disposed of and 92% agreed that it can be safely treated to be converted into fertilizer [35]. In Europe, the survey on UDT showed that 85% of participants consider using urine as fertilizer as a good or very good idea [36]. A different perception was shown in the survey in the Philippines, where 56% and 76% of the participants thought that urine and stools can be used as fertilizer [37]. On the other hand, a moderate enthusiasm of the Australian community for the manual handling of the compost was surveyed; a fraction of the respondents would volunteer to mix compost (67%), add carbon-rich material to it (97%), and harvest it (39%). Interestingly, 37% of the Australian respondents approved of using earthworms as an alternative for manual compost mixing, while 36% disapproved of using them, and 37% were neutral to this idea. Overall, these worldwide surveys show a positive attitude towards composting humanure, especially if it does not compromise the users' time on handling compost. These survey results bring up the opportunity to capitalize on this attitude in the development of novel, user-friendly, and sustainable toilets that involve minimal interaction of the users with the composting process.

5. Methodology

According to the surveys, the possibility of using the aerobic composting (AC) system that requires the continuous handling of the compost heat to achieve optimal moisture, aeration, and a carbon–nitrogen ratio was less attractive than vermicomposting (VC). For this reason, to minimize human intervention in the composting process, a composting chamber was devised in this paper. The chamber controls temperature, oxygen content, and humidity in a way that mimics the natural processes involved in composting with no human intervention. The bioproducts of the worms (worm cast and worm tea) were applied directly to native vegetation adjacent to the composting chamber. This strategy reduced the manual handling of the compost to zero. The details of the design and setup of the composting chambers are presented in this section.

5.1. Vermicomposting Design

Based on survey results, critical design principles, and best practices for composting, different composting chambers were designed, built, and tested to find the best choice of the composting chamber for a micro-flush toilet interface. The focus was placed on systems with an optimal composting rate and minimal human intervention in the composting process.

Due to safety regulations, humanure was not used in this experiment, instead, a recipe for Synthetic Humanure (SMN) was created by mixing 4 parts of sheep manure, 4 parts of liquid pig manure, and 3 parts of chicken manure. This selection was intended to mimic the variable diet of an average human, while the chicken manure provided a high content of urine capturing the contribution of both urine and stool in the humanure. Toilet paper was considered an important contribution to the composting chambers. Paper is a carbon-rich material, so it provides a balance between the carbon and nitrogen content in the compost chamber [39]. To add carbon to the SHM, cardboard samples were cut into 100 mm squared-shaped pieces and compost was sandwiched between the cardboard layers.

Based on the design, the three composting systems labeled as Control (C), Vermi-compost (VC), and Aerobic compost (AC) were placed parallel to each other as shown in Figure 2 (plan view). Final design drawings were drafted using Autodesk Revit, shown in Figure 3. Three identical plywood timber frames, for three composting systems with dimensions of 1100 × 1200 × 660 mm, were constructed. The frames were placed on a concrete slab that had a 200 µm thick plastic sheet at the base, shown in Figure 3a. Plant trays were placed inside the frames and garden mix soil was poured into the trays to fill them up. The plant trays not only provided built-in pots for the plants to grow in but also transferred the load of the compost to the concrete floor. Four different plants in four corners of every tray were planted, as shown in Figure 2. The planted plants were Arum lily (*Zantedeschia Aethiopica*), Carex Evergold (*Carex oshimensis*), Carex Feather falls (*Carex oshimensis*), and Greater Brown Sedge (*Carex Brunnea*). The plants were in the initial stages of their growth.

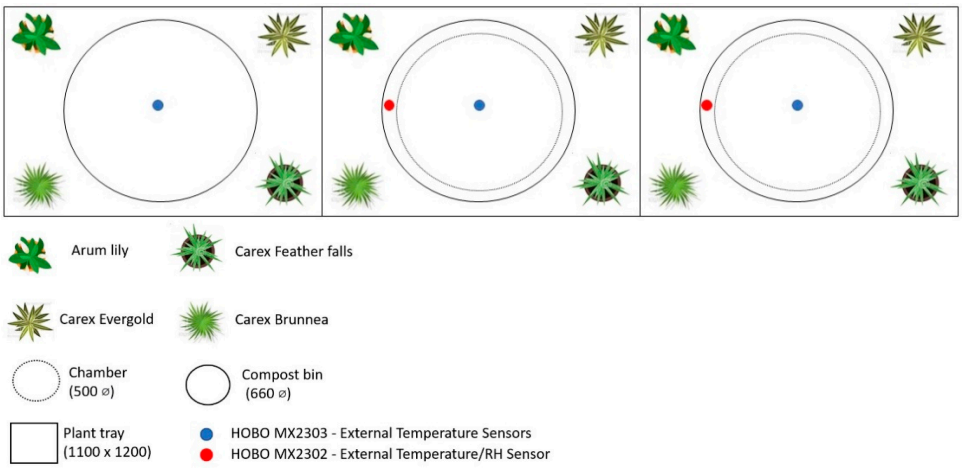


Figure 2. Arrangement of the plants in the corners around the composting systems (left to right): C, AC, and VC. The location points of the plants in each tray were the same, e.g., *Carex Feather falls* was in the bottom right of each plant tray, and *Arum Lilly* was in the top left. The composting chamber was placed only in AC and VC. The location of the sensors for compost temperature, air temperature, and relative humidity is also shown.

5.2. Experimental Set-Up

Three compost systems (C, VC, and AC) were set up, one each in every tray. To protect the chambers from the external environment, they were surrounded by a black plastic bin [40]. The chamber in Figure 3a is a cylindrical steel frame with a steel mesh creating an air layer between the compost and the plastic bin. The air gap created by this three-millimeter wire mesh reduces heat exchange with the environment and improves aeration in the compost. This improved chamber results in more oxygen flowing into the composting chamber and higher temperatures. Inside the steel mesh cylinder, substrate layers were arranged. The layer from bottom to top were hydro corn clay pebbles (50 mm), black silica stone pebbles (50 mm), sand (700 mm), and soil (800 mm). A Geo-fabric sheet was used to avoid mixing the substrate layers. The only difference between VC and AC chambers

was the incorporation of earthworms in the former. The VC chamber had 1000 earthworms poured into the soil layer. The Control compost chamber had only garden mix soil and no substrate layers. A wooden lid top with a fitting of a washbasin sink (mimicking a micro-flush cistern water supply) was installed for both VC and AC up to the manure addition period (up to Day 24). An automated water supply was discharging two liters of water (one-minute duration) to the chambers every day in three intervals (11 am, 2 pm, and 5 pm). The manure was added three times a week (600 mL of chicken, 600 mL of sheep, and 1800 mL of pig) for the first three weeks. Then, 2400 mL each of chicken and sheep were added all together. The composting and vermicomposting took place in AC and VC systems, respectively. The synthetic humanure (SHM) entered the chamber and was processed by earthworms in the topmost bedding layer while the excess liquid was filtered through the chamber geo-filter containing various sands and gravels before being drained out as a more pathogen-free effluent. The same process happened in the AC system but without earthworms.

The arrangement of all the components of the compost bin system is shown in Figure 3. The compost bins were checked from the inside from time to time. The purpose of checking was to make sure the dip in the height of the compost was noted, e.g., on Day 43, the compost height had reduced inside the chambers by 8 and 12 cm in the VC and the AC, respectively. Cross sections of different filtering layers inside the composting bin with manure addition at the top are shown in Figure 3c.

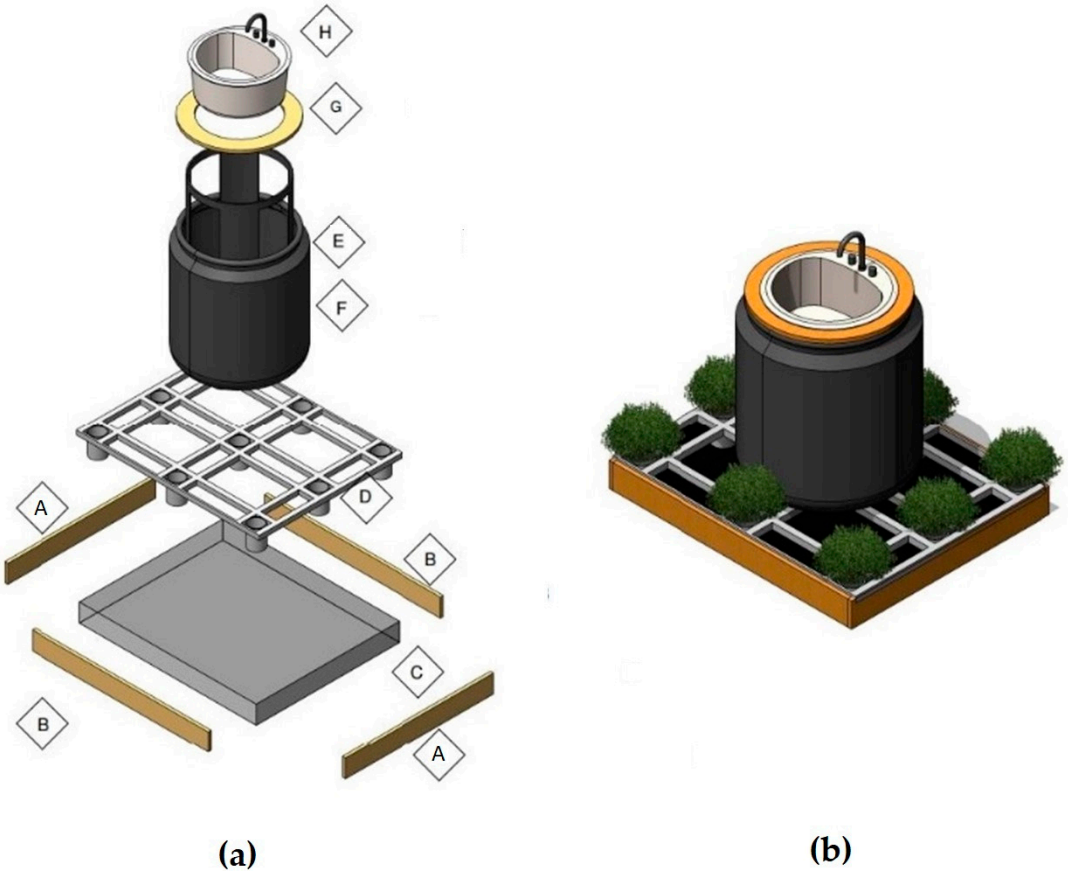


Figure 3. *Cont.*

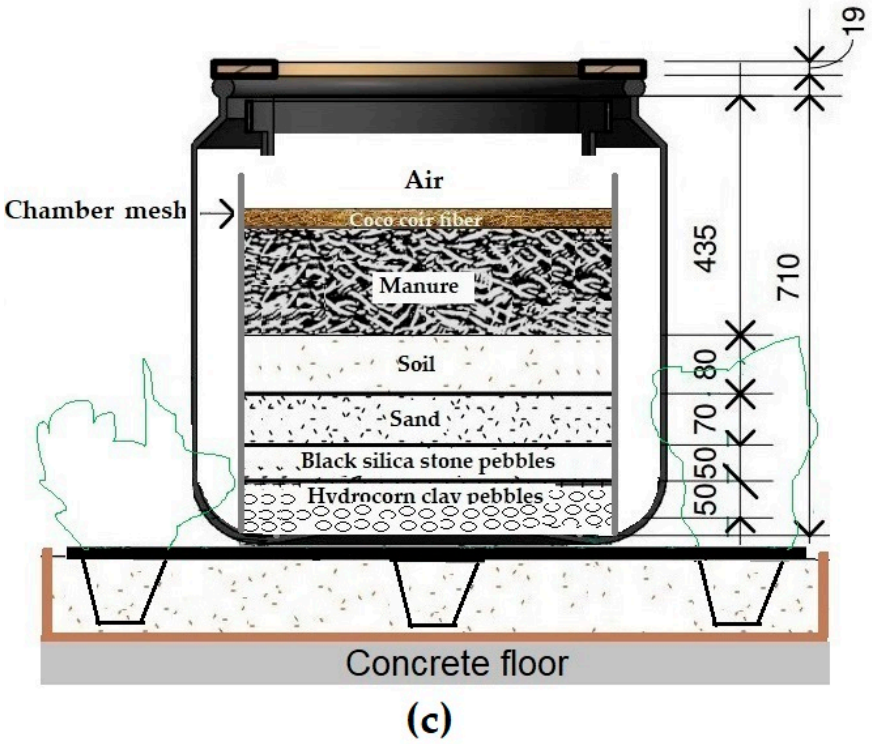


Figure 3. (**a**) Exploded of all the pieces involved in the construction of the composting system. (A) Plywood side walls—lengthwise, (B) Plywood side walls—Breadth wise, (C) Plastic sheet, (D) Plants base for plantation, (E) Steel mesh, (F) Compost bin, (G) Compost lid, (H) Vanity, (**b**) Three-dimensional view of the complete experimental set-up of a chamber. (**c**) Cross section of the composting system showing all the filtering layers (from hydro corn pebbles to soil) in the AC and VC systems. The manure is shown being added on top of the soil layer which merges with the soil. In VC, the earthworms were poured to mix with the soil. The thickness of manure changes with time depending on the addition and filtration. The top surface is covered with a coco-coir fiber layer to avoid excessive oxidation. All the thicknesses are in millimeters (mm).

It is important to understand the reasons behind what type of different tests were conducted for comparison of the composting samples, during, before, and after the experiment shown in Figure 4, as well as the methods used to perform these tests, e.g., compost pile temperature, physiochemical tests, tea bag index, and soil DNA sequencing. The compost pile temperature range indicates different stages of composting [41], e.g., the mesophilic stage between 20 and 40 °C, thermophilic from 45 to 65 °C, and so on. Based on that, the biological activity inside a compost can be determined.

Temperature monitoring helps the identification of the stage of the composting process [42] as it ensures that the composting process is reaching a stable product. The compost pile temperature was monitored through HOBO MX2303 data logger sensors [43]. The physiochemical tests of soil compost included pH, electrical conductivity (EC), total organic carbon (TOC), total nitrogen (TN), ammonia (NH_3), and moisture content (MC). Monitoring the pH of a soil compost is important because it ensures nutrient balance inside the soil for optimal plant growth leading to improved agricultural and gardening outcomes [9]. EC measurements of the compost provide valuable information about the nutrient status and assess the salinity level of the compost [44]. Finding TOC and TN results in understanding the carbon–nitrogen ratio (C:N) of the compost [9] as C:N ratio is essential for finding compost quality, decomposition progress, and nutrient availability, which helps manage the compost in a better way. Finally, finding the ammonia (NH_3) content is significant because it provides insight into the maturity and stability of the compost [45]. Ammonia production is typically high in the early stages of the compost but with time it decreases

because the decomposition process slows down. Also, high levels of ammonia emissions can contribute to air pollution and unpleasant smells. The metabolism of earthworms also produces ammonia [46]. The tea bag index (TBI) testing provides a standardized, economical, and practical approach to assess the decomposition and evaluate the stabilization rates inside a compost pile. Lastly, DNA sequencing technique used was important because it gives taxonomic classification of phylum. It provides valuable insights into the microbial community composition and diversity within the compost. The physiochemical tests, TBI, and DNA sequencing results were obtained through the same techniques mentioned in the greywater system filtering system [47]. The descriptions of the physiochemical test methods used are shown in Appendix A. The detailed method of the tea bag index studies is shown in Appendix B.

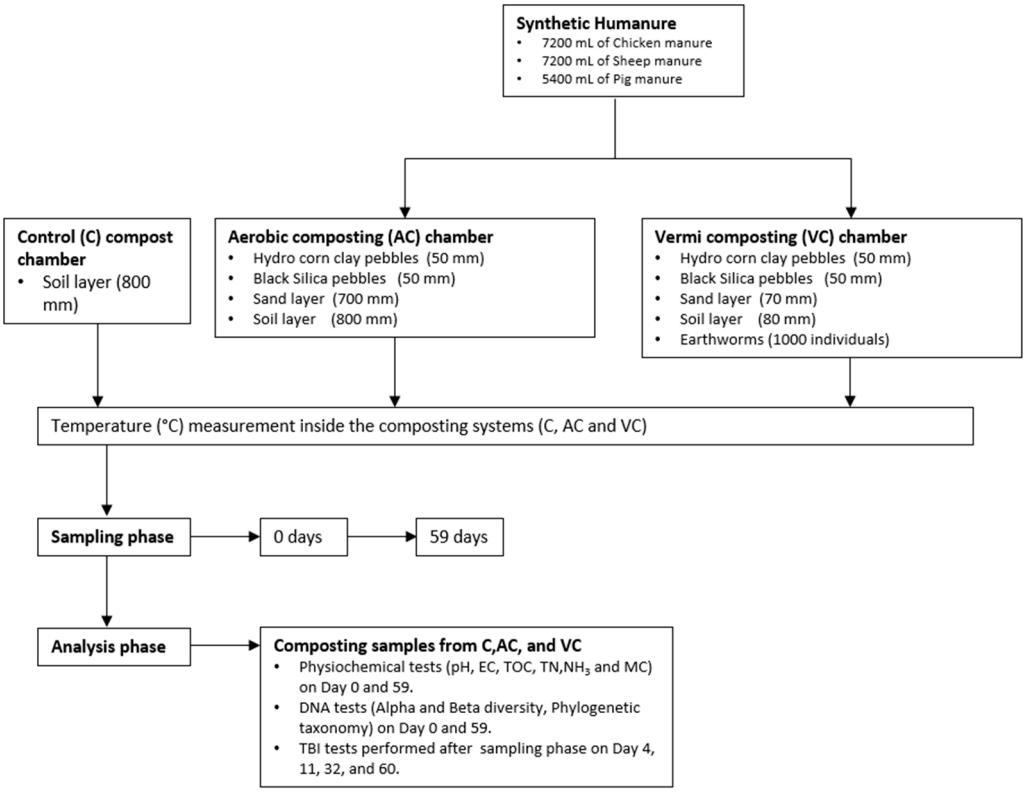


Figure 4. Methodology flowchart of the experimentation. The procedure to obtain the optimal composting chamber is shown in the flowchart and consists of the preparation of the recipe for Synthetic Humanure SHM. Design and building of three composting chambers: control (C), aerobic composting (AC), and vermicomposting (VC), and (the testing of the composting process in the chamber based on compost temperature, Tea Bag Index, physicochemical soil properties, and DNA analysis. The total manure quantity that was added during the experiment is shown in AC and VC composting systems. The layers of materials and their thicknesses are shown for each compost system. The compost temperature was measured inside each system. The sampling phase started on June 27 and ended on August 26, 2022 (59 days). The sampling phase corresponds to the days on which the composting soil samples were taken. The analysis phase included the type of tests conducted on the composting samples collected on specific days from the three composting systems (C, AC, and VC) shown.

In the DNA analysis of the soil, universal primers were used in DNA sequencing for diversity studies. This is because they target conserved regions of the genetic material [48]. Universal primers offer a standardized approach to DNA sequencing, which enables a comparison of diversity across different studies and environments. One commonly used universal primer targeted the 16S rRNA gene in bacteria. This approach is widely used in microbial ecology and environmental studies to assess microbial biodiversity and help

in identifying specific bacterial taxonomy [49]. The technique used for DNA sequencing results is shown in Appendix C.

6. Results

The results are organized into four sections. The first section analyses the compost pile temperature inside each chamber. The second section provides a review of the physio-chemical properties of the composting soil samples. The third section investigates the TBI results, which is followed by the last section on soil DNA analysis.

6.1. Composting Temperature

Figure 5 shows the temperature data inside the composting piles. The VC temperatures reached a maximum of 41.31 °C on Day 41, while the AC temperatures reached a maximum of 35.65 °C on Day 42 at 1:00 h. The mean temperature during the experiment for both VC and AC was 21 °C, which is in the recommended range for VC but not for AC. In VC, the continuous temperature rise was noted from Day 24, when 4810 mL of manure was added. After this addition, the compost pile temperature in VC went past the ideal range for earthworms from Day 39 to Day 45. This resulted in earthworms burrowing because they would not survive in this high temperature. The AC temperature did not achieve the ideal range (45–65 °C) throughout the experiment [50] as the thermophilic phase (>45 °C) [9] was not achieved. Compost requires the cultivation of aerobic, or oxygen-loving, bacteria to ensure thermophilic decomposition [51]. Also, to reach thermophilic phase decomposition, it takes a minimum of 1 m^3 (one cubic meter) of compost [52].

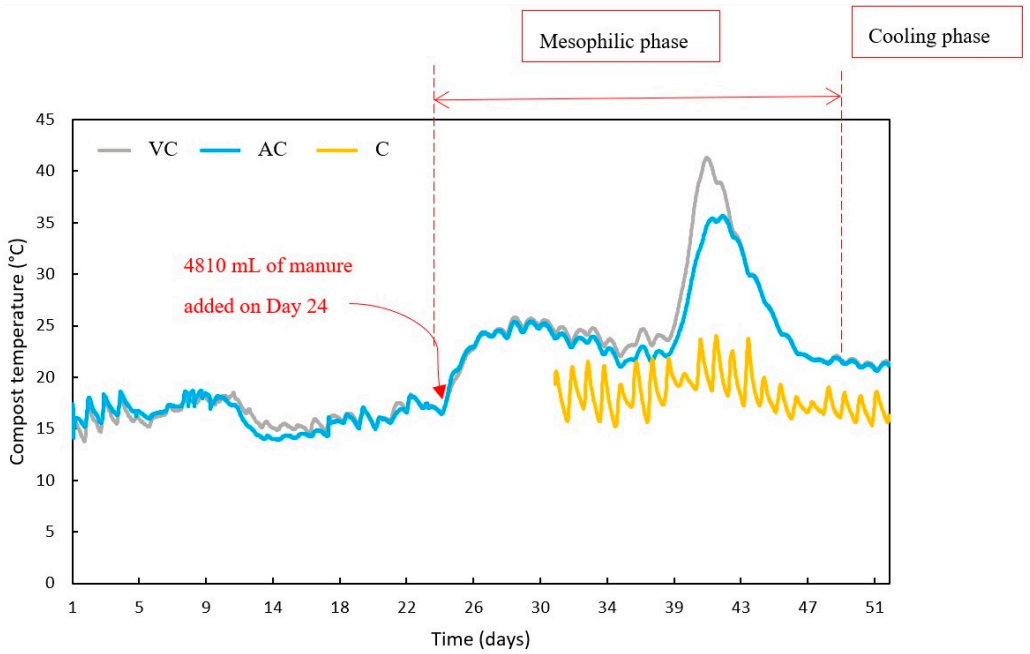


Figure 5. The temperature variation graph inside the composting piles of control (C), aerobic compost (AC), and vermicompost (VC) systems. The data of C compost were recorded from Day 30 to Day 51 (21-day period). From Day 1 to 23, mixed manure (600 mL of chicken, 600 mL of sheep, and 1800 mL of pig) was added with a 2-day frequency. On Day 24, 4810 mL of manure (2400 mL of chicken, 2400 mL of sheep, and 10 mL of pig) was added together, increasing the temperature of the compost to the mesophilic stage. The two phases (mesophilic, and cooling/curing) are highlighted. The mesophilic stage temperature range (20–45 °C) started from Day 24 because 35% of the manure quantity was added to the system altogether.

6.2. Physiochemical Properties of Soil

The before-testing soil (BTS) sample properties were compared with the soil composting samples from C, VC, and AC after the end of the irrigation period (Day 57).

From Figure 6, the effect on soil physicochemical properties of adding the manure into VC and AC composting systems is very clear. All the compared properties have shown higher values for both VC and AC. The experimental period of 59 days in the BTS in the control composting system increased the pH by 0.4 ± 0.08 (Figure 6a). This 5% increase in pH over 59 days has also been found in another study of 60 days [53]. The pH of both VC and AC was slightly alkaline (>7.5); this pH is ideal for the thermophilic phase of composting [54]. If the pH is too acidic or too alkaline, bacterial activity will be hindered or stopped completely. The pH turning into alkaline at the curing phase (Day 59 sample) [9] is normal. Overall, the pH values achieved by both VC and AC were in the desired range (5–8) [9].

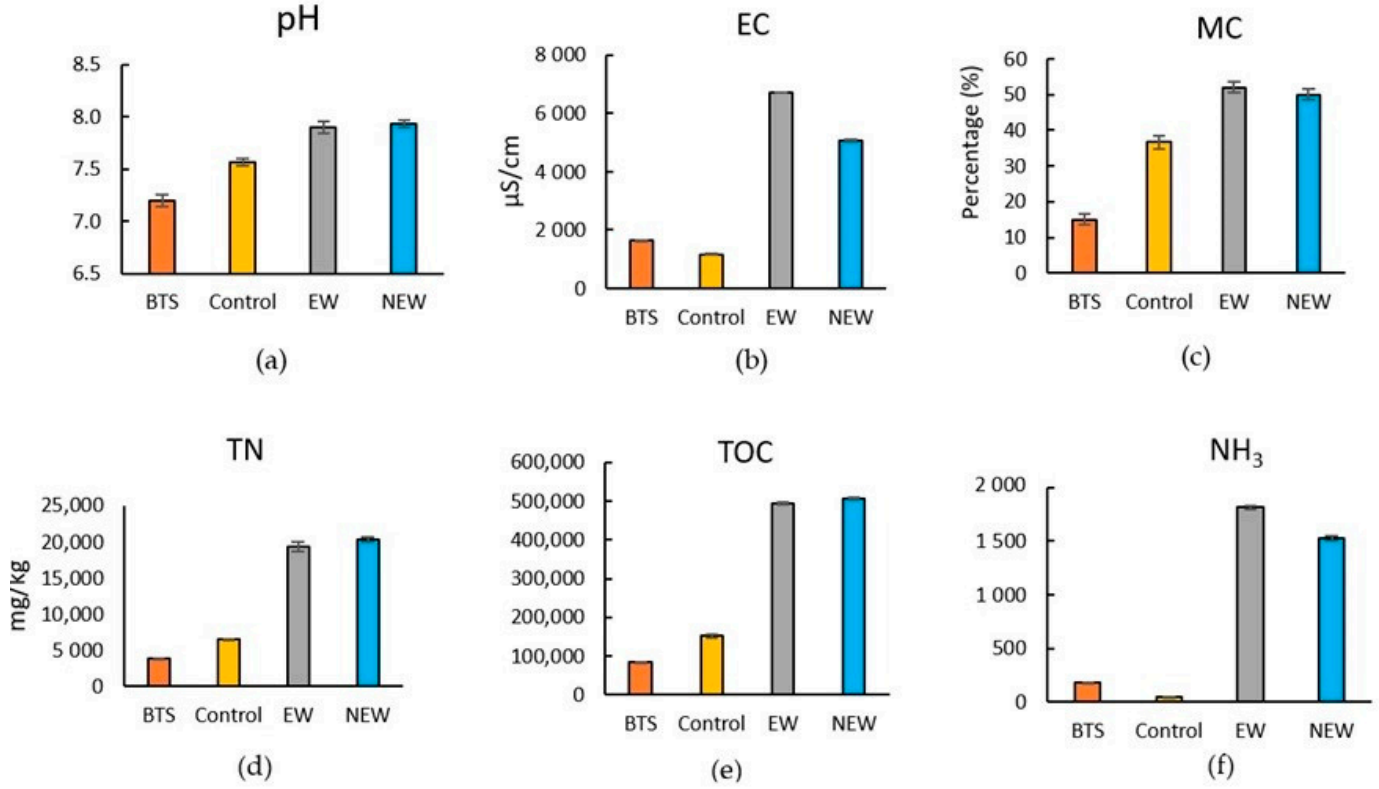


Figure 6. Physiochemical properties of the soil samples before treatment of soil (BTS), control (C), vermicomposting (VC), and aerobic composting (AC) composting systems. The measured quantities are (**a**) pH, (**b**) Electrical conductivity, (**c**) Moisture, (**d**) Total Nitrogen (TN), (**e**) Total organic carbon (TOC), and (**f**) Total ammonia (NH_3). The error bars encode the mean and standard deviation of three subsamples.

The 59 day experimental period of BTS inside the control compost bin decreased the EC by 28% (Figure 6b). The EC values for both AC and VC were above the desired range. AC was only 12% greater than the ideal value (5000 µS/cm) but the EC value in VC was 123% greater than the required value (3000 µS/cm). This high value is due to the nutrient content and other non-essential soluble salts [55] in VC, due to the digestion and mixing by earthworms. A difference of 1633 ± 6.7 µS/cm was noted between VC and AC. In dairy manure-based vermicompost, the EC readings range from 10,000 to 20,000 µS/cm [56]. This high EC value in VC can also be due to water occupying the larger pores and being connected, suggesting that the EC of soil increases when the water content and degree of saturation increase [57].

The moisture content (MC) level in the AC was suitable but below the typical range by 10% in the VC, though earthworms can still operate and decompose organic matter within a broader moisture range [58]. Also, the samples were taken on Day 59, i.e., the MC had decreased by then therefore, overall, the MC level was in the acceptable range (50–60%) [59], as shown in Figure 6c. This MC level was suitable for aerobic degradation [60,61].

The high total nitrogen TN and total organic carbon TOC (shown in Figure 6e,f) can immobilize the soil and degrade pesticides, nitrates, phosphorous, and other chemicals that can become pollutants [9]. The carbon/nitrogen ratio (C:N) calculated was found to be 23:1 for C and 25:1 each for VC and AC. The ratio is in the recommended range of the C:N ratio for a composting pile (20:1 to 35:1.16 [62]). The manure mix (pig, sheep, and chicken) added to the VC and AC systems had a mean C:N value of 15:1 [63]. This means the mixing of the manure with soil and cardboard fencing the composting chamber alongside separating the composting layers increased the C:N ratio of the VC and AC by 66%. A similar increase in the nitrogen cycle was also observed in another incubated composting study [64].

The recommended ammonia (NH_3) levels for both AC and VC should be less than 500 mg/kg [65] but they were found to be 1500 and 1800 mg/kg, respectively, as shown in Figure 6f. The difference was 293 $\pm$ 2 mg/kg. The difference can be attributed to the ammonia produced by the earthworms [66]. This high increase in the NH_3 content of VC and AC is mostly related to the chicken manure because it contains a combination of faeces and urine. The urea present in the urine can be converted into ammonia through a process called urea hydrolysis. A chemical reaction occurs when urea reacts with water, resulting in the breakdown of urea into ammonia (NH_3) and carbon dioxide (CO_2). This reaction is catalyzed by the enzyme urease, which is produced by certain microorganisms [67]. Part of the produced ammonia is further transformed into nitrates (essential soil fertilizers) by nitrifying bacteria. Another part of the ammonia became volatile and produced an unpleasant odor and air pollution. Earthworms are sensitive to high levels of ammonia as it is toxic for them [46]. Therefore, the increase in NH_3 levels caused the increase in the bad odor which resulted in earthworms leaving the VC chamber.

6.3. Teabag Index Studies

The incubation times (t) inside the soil for the teabags were: $t1$ = 0 days, $t2$ = 4 days, $t3$ = 11 days, $t4$ = 25 days, and $t5$ = 60 days. The TBI analysis enabled 48 tea bag index in-field incubations (replicates included) in this project. Only one replicate was neglected because of getting damaged during the withdrawal process from the soil. The ratio of the final weight to the initial weight of green and rooibos tea bags in all the composting systems (C, AC, and VC) is shown in Figure 7. The green tea mass loss averaged 24% in C, and 15% and 20% in AC and VC, respectively. The rooibos tea mass loss averaged 12% in C and 9% each in AC and VC, respectively. This faster decomposition was expected in green tea because it is a leaf material and consists of a more easily degradable material compared with rooibos tea, which is made from wooden shrubs [68,69].

At the beginning of the TBI results ($t4$, $t11$, and $t32$), the decomposition was faster in the C compost compared with the VC and AC. The reason was that microbes in VC and AC have a diverse range of materials to decompose compared with C. But, as the TBI analysis reached $t60$, the decomposition in VC was approximately the same as C, and the fitting curve indicates a further increase in it beyond $t60$. Thus earthworms in the VC chamber fastened the decomposition process, resulting in higher metabolism rates compared with AC [70]. This is also beneficial in decreasing the pile volume [9]. The other reason behind the VC decomposition curve looking similar in shape to the C, in the long run, is that when the earthworms left the compost pile after reaching a plateau after a certain point, means that their rate of activity will slow down or stabilize [71] and their impact on the composting process decreased [72]. The efficiency of organic residue decomposition during VC is directly affected by the biomass and population structure of earthworms [73]. In the course of VC, earthworms ingest organic material, grind it with gizzard, and pass it through the gut [74]. This results in an increase in the active sites for microbial activity in

the substrate. As the microbial activity increases, a portion of the carbon content is lost in the form of CO_2, and, subsequently, the mineral content in the substrate increases [75]. The mineralization of nitrogen occurs, resulting in increased concentrations of nitrate and ammonium. Also, C:N ratios between 20 and 30 are considered suitable for earthworm growth [76]. The results also show that rooibos tea ingredients are hard for worms to digest because the percentage loss is approximately the same. The burrowing of the earthworms in VC due to high temperature and excessive ammonia content with time caused similarity in the results between the VC and C systems.

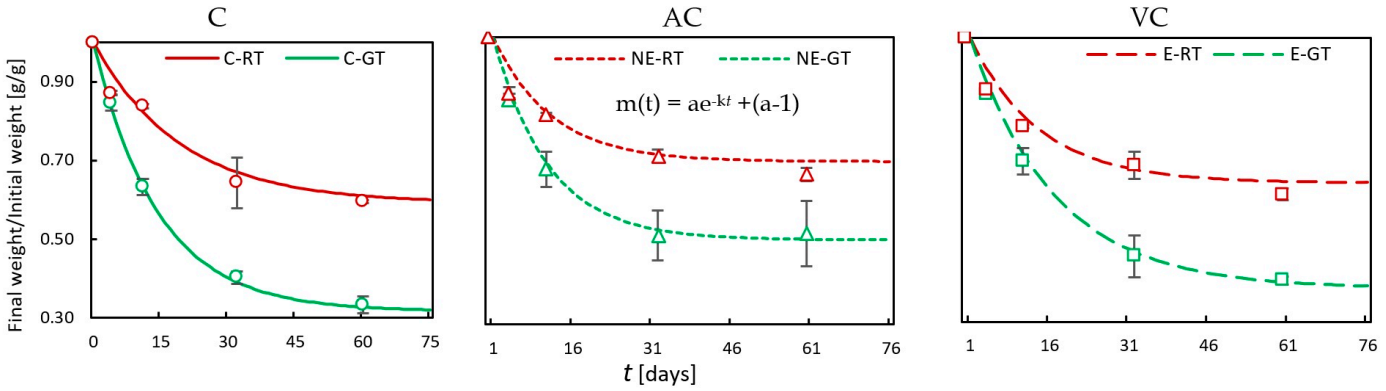


Figure 7. The relative mass of tea bags as measured in laboratory incubations for rooibos tea (RT) and green tea (GT) bags in C, AC, and VC systems. The green line is for GT and the red is for RT. The shapes with error bars are experimental data collected on those specific days and the curve is extrapolated up to 75 days. The equation $m(t) = ae^{-kt} + (a - 1)$ is used for all the curves, here 't' is the incubation time, 'a' is the labile fraction, and 'k' is the decomposition fraction (with 95% confidence bounds). Values are the mean of three replicates and the ± error bars indicate standard error means (SEM).

The constant decomposition rate pattern in all the composting systems is shown in Figure 8. The mean decomposition for the measured incubation times (t) in C and VC was around 0.05 ± 0.01 and, in AC, it was 0.07 ± 0.01. In C and AC, 50% and 40% decreases were noted in 'k' from t4 to t11, respectively but no decrease was noticed in VC from t4 to t11. This lack of change is related to the early settlement period of the vermicompost as vermicompost takes time (up to 2 months) to attain a marked transformation of organic matter to vermicast (work cast and worm tea) [77]. Also, the value of 'k' in VC then decreased steadily by 17% from t11 to t32 to t60. This decrease is related to the high-temperature rise inside the VC chamber because the fatal temperature range for earthworms is between 35 and 48 °C [78]. Therefore, the VC had already reached this temperature range before the tea bags were planted, i.e., the earthworm had left or burrowed by then.

The high stabilization factor in AC indicates that the organic matter of teabags decomposed slowly [68], as microbial breakdown did not easily happen compared with VC. The findings of this study were compared with other studies undertaken in different locations and climates, as shown in Figure 9. This revealed how realistic these findings are. It was noticed that the C and VC stabilization was in the domain of mangroves and mixed forest conditions. Also, the effect of manure makes the compost more stable and suitable to be used as fertile soil. It was noticed that decomposition was high for the composting systems compared with the other studies. The rich microbial diversity increased the decomposition in manure composting systems that were more efficient in increasing the metabolism and promoting soil ecosystem functioning [79]. The stabilization of the C compost and VC were approximately like mangrove forests and mixed forests, respectively. This is because mangrove forests have a high moisture content like the C compost and the mixed forest is rich in soil microbial diversity.

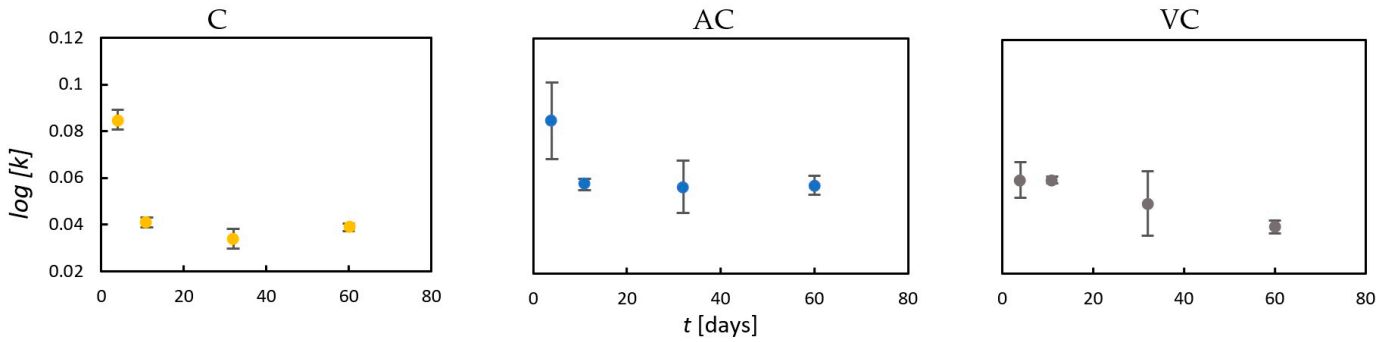


Figure 8. Comparing the constant decomposition rate (k) values for C, AC, and VC composting systems. The *k* was calculated using Equation (A3) shown in Appendix B. The dot points (Yellow, Blue, and Grey) are the mean of three replicates at *t*, and error bars indicate ± SEM.

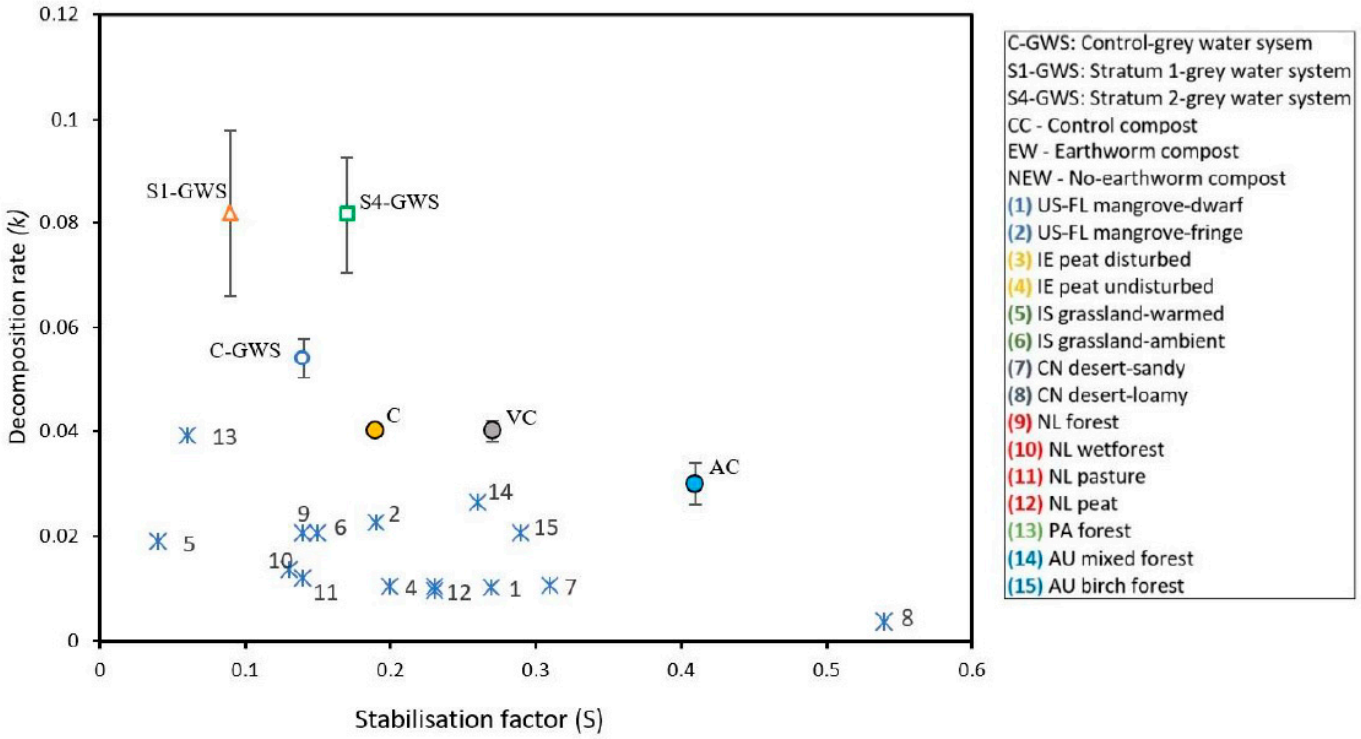


Figure 9. The Decomposition (*k*) and Stabilisation factor (*S*) for experimental data of the compost chambers C, VC, and AC were compared with different case studies from different countries found in the literature. The data points of strata of the greywater-treated system (S1-GWS, C-GWS, S4-GWS) of a wetland staircase research study are also shown [47]. The first step S1 had the maximum greywater concentration and the last step S4 the minimum, compared with the control stratum C, which was fed with tap water only. The incubation time (*t*) was extrapolated to 66 days for all the strata (C, AC, and VC composting systems). Blue asterisks (*) are references to tea bag index (TBI) parameters from different environments, as shown by Keuskamp et al. [68], where the numbers of labels indicate country and ecosystem (United States–Florida = US-FL; China = CN; Panama = PA, the Netherlands = NL; Austria = AU; Ireland = IE; and Iceland = IS). The *t* value for all the other environments varied between 66 and 90 days.

It was also noticed that composts are more stabilized and lower in decomposition compared with the wetland biofiltration systems, shown in Figure 9. There are different factors behind the faster decomposition process in wetland systems compared with compost soil; the wetland had 9–12% of phylum (Acidobacteria, Actinobacteria, Verrucomicrobia, Gemmatimonadetes, etc.) which were less than 2% present in soil manure composts of

AC and VC. Therefore, the rich microbial diversity increased the decomposition in the wetland system and was more efficient in increasing the metabolism and promoting soil ecosystem functioning [79]. Also, moist environments with good aeration can have the fastest decomposition [80], as in wetland plants the soil was moist. Lastly, the presence of certain compounds in the greywater soap may have stimulated the growth of bacteria that were able to decompose organic matter more rapidly, leading to a higher soil decomposition rate in greywater-absorbed soil compared with compost soil.

6.4. DNA Sequencing

The DNA sequencing results were found from a single soil sample taken from BTS, C, AC, and VC, and its α-diversity was examined. A T-test/ANOVA statistical method was used, and the taxonomic level was Feature-level. The Chao 1 diversity index as a measure of species diversity took into account the abundance of individual species in the tested samples [81]. The main difference in specie diversities was the manure because the 59 days' time by BTS in control compost did not increase the species shown in Figure 10a, whereas the manure increased this percentage by approximately 57% in both VC and AC as the estimated richness of species within the two composting systems was similar. This also means the diversity was not affected by earthworms or the addition of manure in VC, and AC was the only reason for the increase in specie richness reaching up to 123 on the index shown in Figure 10a.

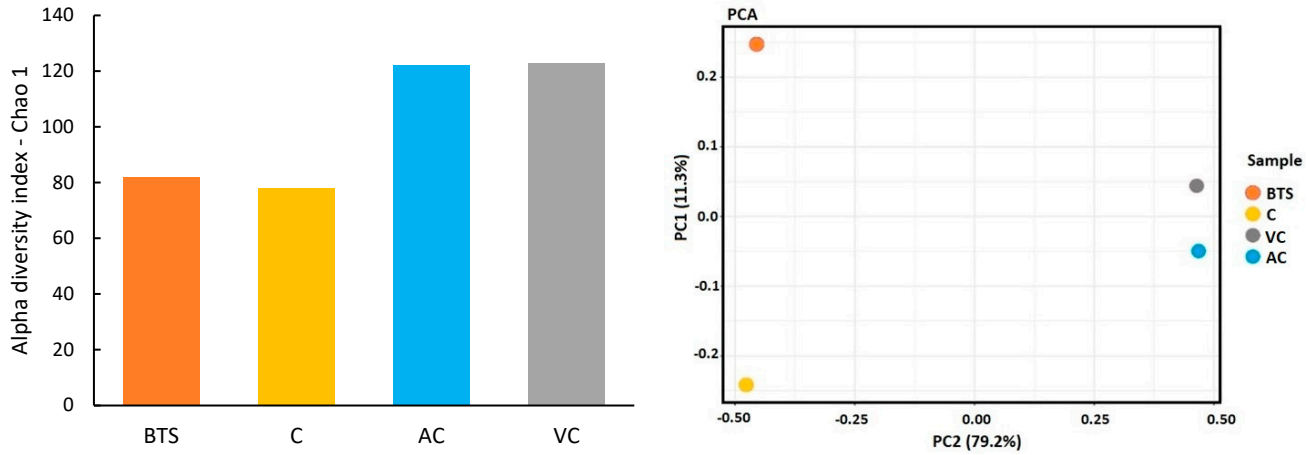


Figure 10. (**a**) Comparing the α-diversity of the before treatment soil (BTS), C, AC, and VC systems using Chao 1 diversity index. (**b**) Comparing the β-diversity using Principal Coordinate Analysis (PCA) shows the variance axis of BTS and composting systems (C, AC, and VC). PC1 reveals the most variation, while PC2 reveals the second most variation. Differences among data points along the PC1 axis are larger than the similar-looking distances along the PC2 axis. Positive loadings indicate a variable and a principal component are positively correlated: an increase in one results in an increase in the other. Negative loadings indicate a negative correlation. In both (**a**,**b**) plots, the AC and VC showed similarities, which reflects the effect of the manure.

Beta diversity differences between all the samples were examined, measuring the diversity between the samples. The principal coordinates analysis (PCA) technique was used to visualize this. PCA is a simple way of showing complex data as it reduces the number of variables while maintaining important information from the data [82]. In Figure 10b, the two main components of the data are represented as Axis 1 (79.2%) and Axis 2 (11.3%) on a 2D graph. The graphs show that BTS and C form a cluster on PC1, whereas VC and AC are also in a cluster form but on PC2. This indicates a clear effect of the manure, while the impact of earthworms was negligible because VC and AC are very close to each other and far from BTS and C.

The actual abundance of different types of phyla in BTS, C, AC, and VC is shown in Figure 11. A total of 105,866 Operational Taxonomic Units [OTU] were retrieved. AC and VC had 87% (43 and 44%) of the total OTUs. The total number of identified phyla was 11. In the taxonomical phylum analysis of VC and AC, the most dominant phyla were Bacteroidetes and Proteobacteria, showing the clear effect of manure. The percentage of Bacteroidetes in the AC and VC was 62% each. Proteobacteria was the second most abundant phylum and was found to be 30% and 32% in AC and VC, respectively. The presence of these phyla also indirectly influences the nitrogen cycle and nitrification processes in compost [83], as they support the growth and activity of nitrifying bacteria in the composting systems in the form of urease-producing bacteria. This bacteria can be found within these phyla, e.g., some species of Proteobacteria, such as Klebsiella and Pseudomonas, are known to produce urease (the enzyme that converts the urea into ammonia) [84]. Similarly, certain species within the phylum Firmicutes, like Bacillus, are also capable of urea hydrolysis [85]. The high nitrification due to ammonia is then fixed back into the soil by ammonia-oxidizing bacteria (AOB) and nitrite-oxidizing bacteria (NOB) [86]. Both AOB and NOB are commonly found within the classes of Beta and Gamma proteobacteria, while the latter is typically found within the class Nitrospira [87], which is also within the phylum Proteobacteria.

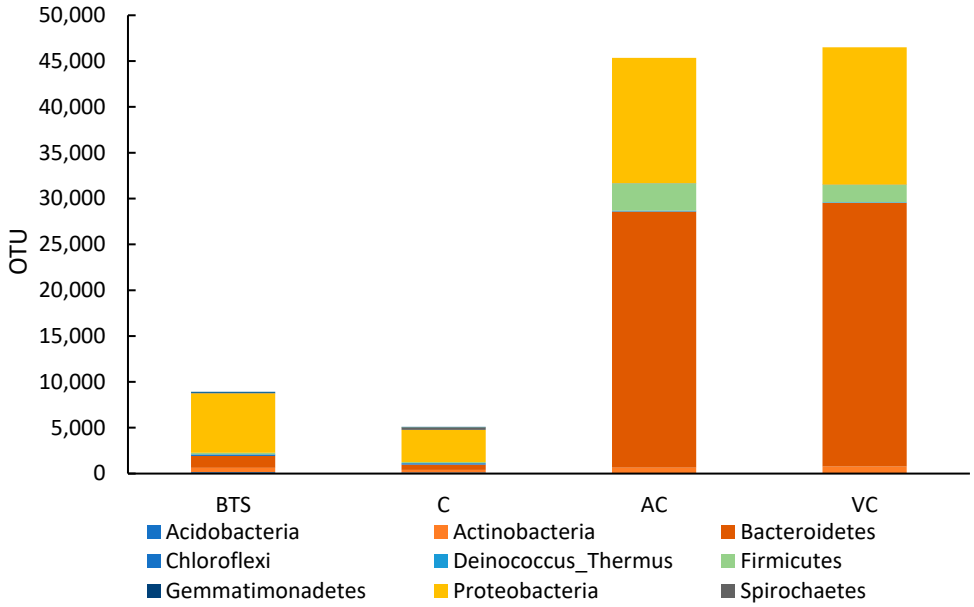


Figure 11. Vertical bar plot displaying Operational Taxonomic Units (OTUs) on the *y*-axis and the phylum-level taxonomy distribution of BTS, C, AC, and VC samples on the *x*-axis. The sampling time difference is 59 days between BTS and the composting systems (C, AC, and VC). The manure addition to AC and VC resulted in high numbers.

Overall, the presence of Bacteroidetes, Proteobacteria, and Firmicutes found in samples is generally considered beneficial for plant growth in a garden mix. However, to detect specific pathogens related to the nitrification and denitrification of bacteria, e.g., fecal coliforms, Salmonella, Campylobacter, Salmonella, etc., additional targeted techniques are required that can identify and quantify each pathogen, e.g., culturing methods, immunological assays, and molecular methods [88]. These methods have distinct approaches with different principles and techniques. Also, to a certain degree, phylogenetic tree analysis can be used [89] to find the ratio between harmful and useful pathogens. This sequencing data can be used for the phylogenetic tree analysis.

A simplified structure of the phylogenetic tree up to the class level is shown in Figure 12. The tree was the same in all samples and only the percentages shown in Figure 11 varied among them. The three were constructed using the national center for biotechnology

information (NCBI) database [90]. Figure 12 shows the categories of different levels of classification being represented hierarchically, starting with the kingdom "Bacteria". From the kingdom Bacteria, three major phyla, Bacteroidetes, Proteobacteria, and Firmicutes, are shown. Each phylum then branches out into more specific groups in the form of class and order. Proteobacteria and Firmicutes have a diverse range of classes, but Bacteroidetes have only one order and no class. All the remaining phyla accounted for only 1–2% of the total taxonomical percentage. Due to their relatively minor representation, these phyla were considered negligible for the scope of this study and were not shown.

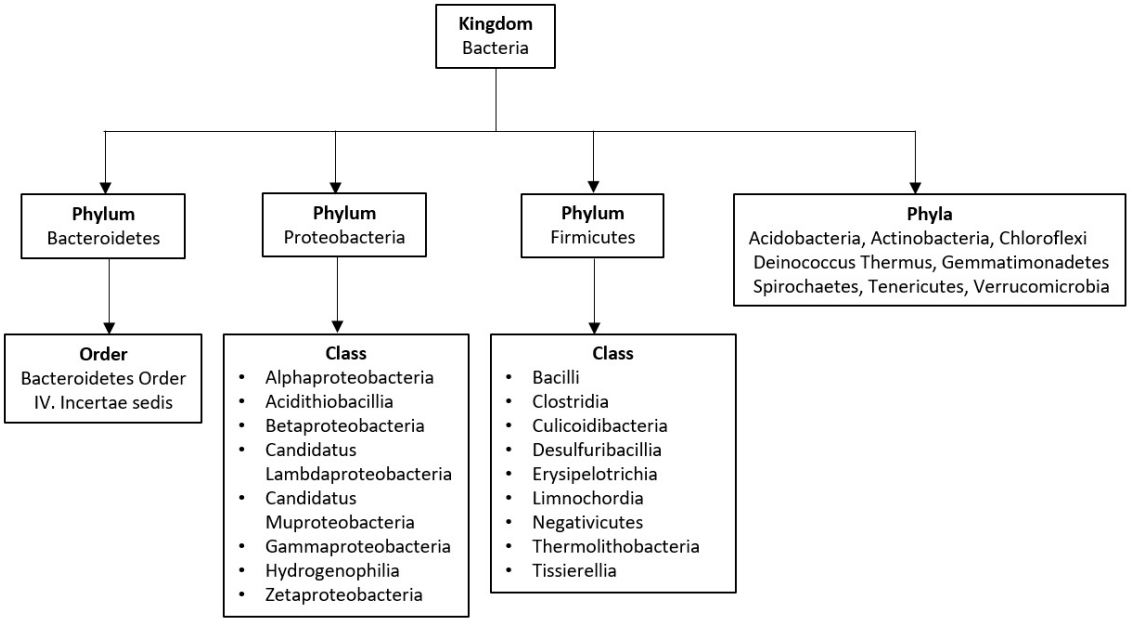


Figure 12. Phylogenetic tree showing taxonomic relationships of the major Bacterial phyla: Bacteroidetes, Proteobacteria, and Firmicutes. All the phyla shown belong to the Bacteria kingdom. Each phylum branches out into respective order and class. The combined Phyla frame accounts for 1–2% of the total taxonomical percentage and is not shown as it is a minor representation.

The compost bin filtering system comprised of different layers was producing filtered liquid fertilized in the end. This fertilizer had a positive impact on the growth of the plants around the composting chambers. The effect of liquid fertilizer on the Carex Feather fall plant was more prominent compared with Carex Gold, as the latter showed very slow progress during the experiment. The maximum plant growth was seen in Arum lily as its leaf numbers increased from one to four. It was evident that the liquid fertilizer can be safely used for ornamental plant irrigation providing a biophilic environment.

7. Discussion

In this paper, we investigated several possibilities to design user-friendly and sustainable toilets by (1) reviewing several surveys on different continents to identify the perception of the societies to the different toilet systems, and (2) building an experimental protocol to investigate the performance of two different composting systems: aerobic composting (AC) and vermicomposting (VC).

The surveys' research aimed to gauge the social acceptance and financial viability of composting toilets. The recommended design revolves around a VC toilet, capable, in theory, of continuously processing waste into valuable compost while conserving water through a micro-flush interface and operating without manual handling. The results of the conducted surveys across different continents regarding the acceptance of composting toilets or urine-diverting toilets in homes or outside their homes revealed that most of the users are willing to adopt these toilet technologies. Based on the targeted questions

related to willingness, this percentage was quite high in Europe and it was relatively low in Australia. In the United States, the percentages were high when the users were given a choice of free installations, if not then the percentages dipped considerably. In the Philippines, the order of priorities was water saving, economic costs, and the recovery of fertilizers.

An experimental investigation into the performance of AC and VC chambers was conducted and compared with the performance of a control C chamber. The results summarized in Table 1 revealed that composting significantly increased the temperature of the chambers, and due to earthworms' metabolism in VC during the mesophilic stage, the mean compost temperature was 2 °C higher compared with AC compost. Also, in VC, the temperature exceeded the ideal range for the worms, and it created unfavorable conditions for the earthworms. As shown in Table 1, the physicochemical properties of the soil were approximately the same for both VC and AC. It held a remarkably large amount of ammonia in the compost bin due to the activity of both microbes and earthworms, creating an inhospitable condition for the earthworms.

Table 1. Aerobic Composting versus Vermicomposting Analysis.

Metrics	Aerobic Composting		Vermi Composting	
	(Ideal) Range	**Experimental**	**(Ideal) Range**	**Experimental**
Temperature	49–71 °C	14–36 °C (21 °C)	13–25 °C	14–41 °C (21 °C)
Electrical conductivity	1000–5000 µS/cm	5600 µS/cm	1000–3000 µS/cm	6700 µS/cm
Moisture content	40–60%	50%	60–80%	52%
Carbon–Nitrogen ratio	25:1–30:1	25:1	20:1–30:1	25:1
pH	6–8	7.9	5–8	7.9
NH_3	<500 mg/kg	1523 mg/kg	<500 mg/kg	1817 mg/kg

The TBI studies revealed that VC compost decomposition and stabilization were closer to the C compost in the longer run. In the beginning, the decomposition in the control chamber was faster but, with time, as the earthworms settled and slowly burrowed in the compost bin, the decomposition became the same as the C. The AC achieved maximum stabilization by day 60. The microbial activity was different than in wetland systems. The composting chamber showed a lower decomposition rate than in wetlands. A clear distinction in the stabilization index was observed from the TBI analysis; the level stabilization was ranked from smallest to largest in wetlands, control, vermicompost, and aerobic compost.

The results clearly showed that the diversities of species (α and β) were influenced by the manure usage because the period of 59 days without manure in the compost bin did not have a significant impact on the diversities, as the BTS and C samples had the same findings. In VC and AC, the most prevalent microbes were Bacteroidetes and Proteobacteria. This highlights the importance of manure in shaping the microbes' percentages in compost, which are interconnected with the potential effect of the nitrogen cycle. The data obtained from this current research will serve as a solid foundation for future investigations.

The use of earthworms in the vermicomposting process to reduce manual handling possess several challenges. This is because the composting activity produces high temperatures and a high level of ammonia content that creates an unfavorable environment for the earthworms. There are several alternatives to alleviate these issues, such as using larger compost chambers with high levels of ventilation to allow sufficient temperature zones for thermophilic and mesophilic bacteria and earthworms to thrive. The use of geotextiles to separate the different layers in the VC creates difficulties for the worms to migrate to the different levels of the compost. To overcome this issue, it is recommendable to design special *worm elevators*, which are vertical channels connecting the substrates. These elevators would allow the worms to surface and burrow according to the temperature and ammonia levels of the compost. Last but not least, it is imperative to design systems to separate urine

and stool without user intervention. Both byproducts should be treated by two separate composting chambers: *VC* treating the stools and *urea-filters* treating the urine.

Two candidates for future toilet systems are shown in Figure 13. The urine-diverted flush toilets should capitalize on the recent advancement in Swedish technologies, such as the urine-separated flush toilet interface [36], the aquatron separator of stool and water [91], and the sealing membrane and blue traps for waterless urinals [92]. The blue traps have a density lower than urine so they can effectively seal its unpleasant odors. The urine passes through the sealing membrane, which then closes when the urine flow stops and effectively seals the urine outlet, preventing smell, as shown in Figure 13a. Stools have low levels of nutrients and high contents of bacteria that may be more favorable for the earthworm activity in the VC. The aquatron separates stools from water using centrifugal forces. The stools fall into a compost pile and the water can be directed either to the sewage or to a wetland system, see Figure 13a. On the other hand, the urine contains urea as a valuable fertilizer and a low level of bacteria making it almost sterile, so it should be treated separately by a urea-filter. When distilled by passive strategies such as solar radiation, urea can be stabilized and straightforwardly converted into fertilizer.

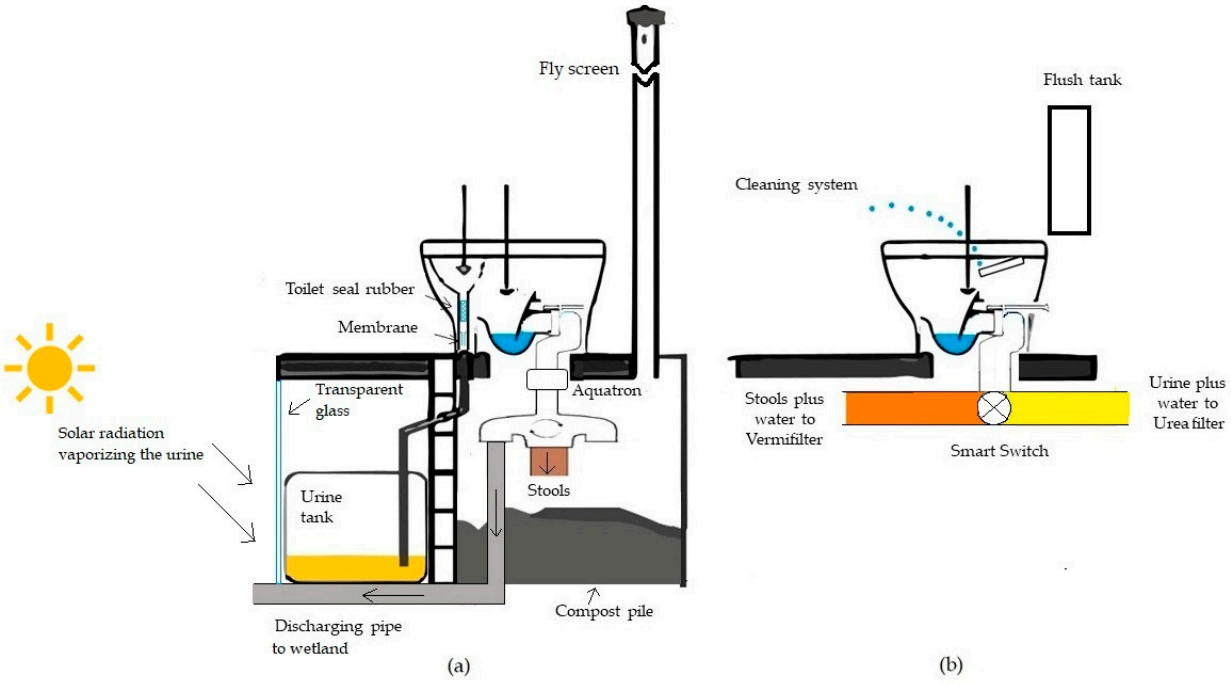


Figure 13. (**a**) Swedish toilet interface showing separate urine collection. The water in the urine evaporates and leaves the phosphorous, nitrogen, and potassium content. The aquatron operates to direct the stool to the compost pile and the greywater is discharged through a pipe toward the sewer or wetland filtering system. (**b**) The Japanese toilet concept design and the future version of the vermi/urea filters. These should operate from a Smart Switch separating the urine from the stools and it directs the urine and stools to the ureafilter and the vermifilter.

A second candidate for toilet systems is shown in Figure 13b. This is a design inspired by the Japanese systems that embrace the technology of Smart Toilets and focus on the comfort and positive experience of the user [34]. The advanced and commercially available TOTO micro-flush toilets can be connected to a VC and urea-filter by a Smart Switch, shown in Figure 13b. Based on the optical analysis, the Smart Switch should detect whether the flushed material contains stool and consequently divert the flush either to the VC or the urea-filter. Different from the Swedish system, the urine in this system will be mixed with water so that it is more reasonable to directly apply this mixture to a bed of nitrogen-hungry plants for recovering nutrients in the food chain.

This study does not provide a final answer on the suitability of a sustainable and user-friendly toilet system. However, it does provide future directions on the design of the sustainable toilet, aiming to minimize human intervention and create a biophilic environment around the urban environment. In this environment, valuable nutrients can be safely returned to the ecosystem through efficient biological filtration. These insights pave the way for potential advancements in sustainable toilet technology.

8. Conclusions

This paper examined surveys conducted across different continents found in the literature. The surveys aimed to gauge the acceptance of composting toilets or urine-diverting toilets. It was found that most users had positive acceptance and willingness to adopt the mentioned toilets but the percentage varied, e.g., in the US, two locations had percentages of 63% and 46% but in Australia, it was 30%. The composting chamber was then designed and the experimental methodology and investigations shed light on the composting processes, demonstrating a difference of 6 °C between VC and AC chambers during the mesophilic stage. The physicochemical properties of both AC and VC samples exhibited similarities. However, both were noticeably distinct from the properties observed in C compost due to the addition of manure.

The other noteworthy findings indicate that the VC decomposition rate closely resembled the C compost in the longer run as, by day 60 for both VC and C, the decomposition rate was approximately 0.04. This underscores the potential effectiveness of vermicomposting for organic waste management. Also, the DNA sequencing results revealed the same type of phylogenetic taxonomy for both AC and VC with the domination of Bacteroidetes (62%) and Proteobacteria (32%). The presence of these phyla influences the nitrogen cycle and nitrification processes in compost.

Based on these valuable insights, this study suggests two promising candidates for future toilet systems. One approach could leverage recent Swedish technological advancements in urine-diverted flush toilets, while another design inspired by Japanese Smart Toilet technology holds promise. These innovative designs pave the way for sustainable toilets, where essential nutrients can be safely returned to the ecosystem through efficient biological filtration.

Author Contributions: The authors' contributions are as follows: conceptualization, F.A.-M. and J.N.; methodology, G.Q., J.N. and F.A.-M.; validation, G.Q., V.P. and F.A.-M.; formal analysis, G.Q.; investigation, G.Q.; data curation, G.Q.; writing—reviewing and editing, G.Q. and F.A.-M.; visualization, G.Q. and F.A.-M., supervision, F.A.-M. and A.B.; project administration, G.Q., J.N. and F.A.-M. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement: Not applicable.

Data Availability Statement: Data is available on request.

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Conflicts of Interest: All authors have no conflict of interest.

Appendix A. Physiochemical Test Methods Used to Find the Compost Properties

pH	Measured using pH meter and electrode in accordance with American Public Health Association (APHA) latest edition, 4500-H+.
Electrical conductivity (EC)	Measured using a conductivity cell at 25 °C in accordance with APHA latest edition 2510 and Rayment and Lyons.
Moisture content (MC)	Determined by heating at 105 ± 5 °C for a minimum of 12 h.
Total organic carbon (TOC)	A titrimetric method that measures the oxidizable organic content of soils.
Total Nitrogen (TN)	Calculated as the sum of TKN (Total Kjeldahl Nitrogen) and oxidized nitrogen. Alternatively analyzed using combustion and chemiluminescence.
Ammonia (NH_3)	Ammonia—determined colourimetrically, based on APHA latest edition 4500-NH_3 F. Waters samples are filtered on receipt prior to analysis. Soils are analyzed following a potassium chloride (KCl) extraction

Appendix B. Tea Bag Index (TBI) Method

The TBI method assumes that any litter incorporated into the soil consists of a labile (decomposable) and a recalcitrant (stable) fraction. Let M_0 be the initial mass of the litter and M_t its mass at time t to define the mass fraction as $m(t) = M_0/M_t$. The decomposition is assumed to obey an exponential law with two reaction rates [93]:

$$m = a\, e^{-kt} + (1 - a)e^{-k't} \tag{A1}$$

where a is the labile fraction, k is the decomposition rate of the labile fraction, (1 − a) is the recalcitrant fraction, and k' is the decomposition rate of the recalcitrant fraction. The reaction rate of the recalcitrant fraction k' is considered to be small in comparison with the labile fraction k, so that for small times $(k't << 1)$ Equation (A1) can be reduced to

$$m(t) = ae^{-kt} + (1 - a) \tag{A2}$$

The TBI method used two different litters: the green tea, a labile litter, and the rooibos, a more recalcitrant litter. They show contrasting decomposition rates. We use subindexes "g" and "r" to encode the parameters of the green tea and the rooibos tea.

The parameter of the exponential model of Equation (A2) was obtained using non-linear regression. The range of values for variables 'a' and 'k' of Equation (A2) was generated. Based on that range, the best possible fit was plotted. The generated curve touched most of the experimentally plotted points and inferred values of a function where no experimental data were available.

If k is assumed constant, it can be obtained by isolating it from Equation (A2):

$$k = \frac{1}{t}\ \ln\left[\frac{a}{m(t) - (1 - a)}\right] \tag{A3}$$

During this decomposition, some parts of the labile compounds stabilize and become recalcitrant tea [94]. Environmental factors play an important role in this stabilization [95] resulting in a deviation of the actual decomposed fraction (i.e., limit value) 'a' from the hydrolysable (i.e., chemically labile) fraction H. This aberration can be interpreted as the suppressing effect of the environmental conditions on the decomposition of the labile fraction and will be referred to as stabilisation factor S:

The stabilization factor (S) was calculated as follows [68]:

$$S = 1 - \frac{a_g}{H_g} \tag{A4}$$

where H_g is the hydrolysable fraction of the green tea equal to 0.842. This constant value of H_g for green tea was quantified using the method proposed by Van Soest [96], in which

the use of two detergents divides the plant cells into less digestible cell walls and mostly digestible cell contents (contains starch and sugars).

The decomposable fraction of rooibos tea was a_r predicted as follows:

$$a_r = H_r\ (1 - S) \tag{A5}$$

where H_r hydrolysable fraction is constant of rooibos tea.

Appendix C. DNA Extraction Technique Used in the Metagen Lab Queensland

The 16S rRNA gene sequencing technique used for DNA extraction in this soil study was used for the identification, classification, and quantitation of microbes [97]. The DNA of each stratum was extracted from 10 g subsamples of soil using a modification of the modular universal DNA extraction protocol [98]. Briefly, this involved 10 g soil samples being mixed with sterile garnet sand and lysis buffer before being processed in a SPEX 2010 Geno Grinder homogenizer (SPEX SamplePrep, Metuchen, NJ, USA) at 1700 strokes per minute for 10 min. After centrifugation to remove soil particles, 9 mL of the supernatant was treated with a flocculant solution designed to remove humic acid contaminants. Samples were again centrifuged, and DNA was recovered from 10 mL of the supernatant using SPRI beads [99]. The purified DNA was then eluted in 200 µL of Tris-HCl pH 8.0 and was assessed for yield and quality using the Quantifluor dsDNA system (Promega, MI, Madison, WI, USA) and agarose gel electrophoresis.

The metabarcoding of eukaryotic and bacterial/archaeal communities was conducted using the primer sets NF1/18S2rB [100] and Pro341F/Pro805R [101], respectively. A two-step PCR protocol was used to generate dual-indexed amplicons adapted from the Illumina protocol for 16S Metagenomic Sequencing Library Preparation. The naïve Bayesian Classifier was used to assign taxonomy to the genus level for the 16S amplicon with version 128 of the Silva reference database [102].

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Knowledge, Attitude, and Practices toward Plastic Pollution among Malaysians: Implications for Minimizing Plastic Use and Pollution

Ka Ker Coco Chin [1], Janardan Mahanta [2] and Tapan Kumar Nath [1,*]

[1] School of Environmental and Geographical Sciences, University of Nottingham Malaysia, Semenyih 43500, Malaysia
[2] Department of Statistics, University of Chittagong, Chittagong 4331, Bangladesh
* Correspondence: tapan.nath@nottingham.edu.my

Abstract: Excessive production, consumption, and indiscriminate disposal of plastic waste contribute to plastic pollution, which has a negative impact on the environment and human health. The KAP (knowledge, attitude, and practices) study is thought to be useful in mitigating plastic pollution because understanding the public's knowledge, attitude, and practices toward plastic pollution can help identify problems and challenges, allowing appropriate policy decisions to be made to set up plans or implement interventions. This study assesses Malaysians' level of knowledge, attitude, and practices toward plastic pollution, as well as the variation of plastic pollution related to KAP among various socio-demographic groups. For this study, an online survey received 294 valid responses. Descriptive statistics, KAP scoring, and response cross-tabulation were calculated. This study received 294 valid responses via an online survey. Descriptive statistics, KAP scoring, and response cross-tabulation were estimated. A one-way analysis of variance, paired t-test, and binary logistic regressions was performed. Respondents' overall knowledge score (95% CI mean score: 3.88–10.94 on a scale of 11) and practice score (95% CI 1.09–6.53 on a scale of 6) were poor across socio-demographics when a cut point of 80% was used. Older (>46 years) respondents seemed to have more knowledge than younger (18–30 years) respondents (odds ratio, OR 4.304; $p < 0.01$). However, respondents between the ages of 31 and 45 reported significantly ($p < 0.01$) higher attitudes (OR 4.019) and practices (OR 4.056; $p < 0.05$). Respondents with environmental-related university education had a higher likelihood of knowing about plastic pollution (OR 10.343; $p < 0.01$). To encourage good practices toward minimizing plastic use and pollution, conclusions are drawn about undertaking interventions such as raising environmental awareness, incorporating plastic pollution topics into formal and informal education, and providing recycling facilities in nearby communities.

Keywords: plastic pollution; waste management; environmental behavior; recycling

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1. Introduction

People widely use plastic products because they are durable, inexpensive, and lightweight, resulting in the widespread use and disposal of plastic products [1]. Their excessive production and consumption have caused plastic pollution that impacts both society and the environment [1,2]. For instance, the annual global production of plastic has increased by around 200 times from the year 1950 to 2015 [3]. Between 1950 and 2015, about 8.3 billion metric tons of virgin plastics were produced worldwide, of which 6.4 billion metric tons were used and disposed of [3]. Another report has stated that the annual production of plastic doubled from 156 metric tons to 353 metric tons between 2000 and 2019 [4]. About 79% of disposed plastics were dropped in landfills, followed by recycling (9%) and incineration (12%) [3]. Besides that, the recent emergence of the COVID-19 pandemic also caused an increase in the usage of single-use plastics and personal protective equipment

(PPE) such as gloves and face masks, which also contribute to both macro- and microplastic pollution [5–7]. For instance, the production of face masks in China increased to 116 million per day in February 2020, which was 12 times higher than that of the pre-COVID-19 pandemic [5].

Plastic affects the environment and human health at every stage of its lifecycle, which includes the extraction and transportation of raw materials, the manufacturing of plastic products, the usage of plastics, and finally, the management of plastic waste [8]. The most visible impacts of plastic pollution are the ingestion, suffocation, and entanglement of plastic debris by animals [9]. Ingestion and accumulation of plastic in the gut can cause obstruction and inflammation in many organs in a wide range of living creatures [10]. Furthermore, larger plastic waste can degrade into plastic fragments like micro- or nanoplastics and enter food chains, leading to bioaccumulation and biomagnification of toxicity in higher trophic-level predators [10]. These plastic fragments can enter the human body through consumption via food or water and inhalation via air [11]. Past studies also show that plastic fragments can be found in human stools [12], and recent research shows that microplastics are found in human blood for the first time [11]. Moreover, the disposal of plastic waste in landfills and domestic burning systems can lead to climate change, air pollution, and soil pollution [8,13]. For instance, the burning of plastic waste with polyvinyl chloride (PVC) contributes to dioxin emissions, and this persistent and bio-accumulative toxin can lead to air or soil pollution [8]. The wider use of plastic products has implications for the overall policy of sustainable development because plastic pollution has become a symbol of an environmental crisis [14].

Malaysia is one of the largest plastic production countries in the world, with over 1300 plastic manufacturers [15]. It produces around 0.5–1.9 kg per capita per day of municipal waste, with plastic waste being the second highest (24%) among different types of waste [16–19]. Besides, Malaysia depends heavily on the disposal of waste in landfills and domestic burning systems, which can cause increased plastic pollution with detrimental impacts on the environment and human health. In addition, Malaysia also has a very low recycling rate, which is inadequate for dealing with the amount of plastic waste produced [20].

Even though people's understanding of plastic pollution has increased due to social practices, the production and consumption of plastic products still prevail [21,22]. Based on a review of people's perceptions of plastic pollution, Heidbreder et al. [1] reported that people value and use plastic despite its potential harm to the environment. There is no consensus on how to solve plastic pollution [23]. There are several suggestions, such as the use of alternatives, such as reusable water bottles and bags made of alternative materials like glass or biodegradable materials and cloth [24], and the sensible use of plastics (reduction, proper handling, and recycling) to minimize plastic pollution [23,25]. However, people's behaviour (e.g., "throwaway culture") connected to single-used plastic items without caring about the environment is regarded as a major concern for plastic pollution [24]. There has been very little attention paid to people's attitudes or behaviours about the hazards of plastic when interventions are designed for the reduction of plastic problems [26]. People having relevant knowledge is recognized as an important and influential factor affecting behaviour, practices, and the implementation of recycling programs [27,28]. It has been reported that attitudes and knowledge related to plastic pollution can influence people's behaviour [29].

The KAP (knowledge, attitude, and practices) study is believed to be useful in mitigating plastic pollution, as understanding the knowledge, attitude, and practices of the public towards plastic pollution can help people understand more about their immediate surroundings and respect environmental issues so that local authorities can proceed with segmentation and channel mitigation efforts effectively [16]. It is a representative tool used to measure the extent of a known situation for a specific population, such as their knowledge gaps, cultural beliefs, and behavioural patterns [30]. This also allows us to identify their current needs, problems, and challenges, which helps us set plans or implement intervention priorities and make decisions. Besides that, the KAP study allows us to

deepen our understanding of commonly known KAP factors that influence behaviour [30]. It investigates human behaviour in relation to a specific topic and identifies what people understand about it (knowledge), how they feel about it (attitude), and how they put their knowledge and attitude into action (practice) [31,32]. Even though it was extensively used in population studies, KAP is now often used in environmental studies [33,34].

Some recent research has investigated the KAP of Malaysians towards domestic waste management and recycling [35–37], the KAP of Malaysians towards sustainable consumption [33], waste management [34,35], and the determinants of the behaviour and perspective of the public towards plastic management [2,16]. These studies found that university students have a moderate level of knowledge, awareness, and practice when it comes to domestic waste management; a high level of knowledge but a moderate level of attitude and practice when it comes to sustainable consumption; good knowledge, a positive attitude, and less practice when it comes to open-burning problems; and more positive and supportive attitudes toward plastic recycling and the ban on single-use plastics.

Outside Malaysia, Srinivasan et al. [38] and Khanam et al. [39] reported that the majority of the sample students in India know about plastic pollution and have a positive attitude towards giving up plastic use, but only one-third of them show good practice. Kenyan youths perceive single-use plastics as a serious environmental and health issue and are willing to switch to reusable alternatives [40].

In Malaysia, we found no previous research that assessed the knowledge, attitude, and practices of the public towards plastic pollution. Therefore, this study was conducted with the following objectives:

(1) To assess the level of knowledge, attitude, and practices towards plastic pollution among Malaysians aged 18 years and above, and
(2) To understand the socio-demographic factors that influence respondents' perceptions of plastic pollution related to KAP. These socio-demographic factors include gender, age, education, and occupation.

This research paper is based on an undergraduate thesis (Knowledge, Attitude, and Practice towards Plastic Pollution among Residents of Malaysia: Across-sectional study) submitted to the University of Nottingham Malaysia 2022, and the copyright belongs to the first author of this article. It is anticipated that the findings of this study will provide useful information for waste management authorities to take action towards reducing plastic use and pollution in the country.

2. Materials and Methods

2.1. Data Collection Approach

An online survey was conducted to understand the KAP among the residents of Malaysia aged 18 years and older towards plastic pollution. A structured questionnaire was developed for this study based on our prior experience and the following [15–17,24,41]. The draft questionnaire was reviewed by three researchers and pre-tested with 10 respondents. Based on the feedback, some questions were added, eliminated, or rephrased for clarity. The final questionnaire consisted of 33 multiple-choice questions in four sections: (1) socio-demographic information; (2) knowledge of plastic pollution; (3) attitude towards plastic pollution measures; and (4) practices towards plastic use and pollution reduction (Table S1). The questionnaire was prepared in English.

The study population for this study was both Malaysian and non-Malaysian residents living in Malaysia during the study period and aged 18 years and above. A Google form link was shared through email and social media platforms such as Facebook, Messenger, WhatsApp, Instagram, and Telegram. Respondents were asked to share the link with friends and relatives to achieve a snowball sample. The form was available from 29 November 2021 to 15 February 2022, and 302 responses were obtained.

This study was reviewed and approved by the University of Nottingham Malaysia Science and Engineering Research Ethics Committee (Application Identification Number: CKKC151121). Participation in this survey was voluntary and anonymous, and respondents

were informed that they could withdraw from the study at any time. Respondents' online consent was ensured with the following statement: "I read the brief information on study objectives and provided my consent to participate in the survey."

2.2. Data Analysis

Descriptive statistics (frequency and percentage), KAP scoring, and cross-tabulation of responses were estimated. For KAP scoring, 1 mark was given when respondents answered the question correctly/"yes", 0.5 was given when they answered "maybe/sometimes", and 0 mark was given when they answered the question wrongly/"no". As for the cross-tabulation of KAP status, an 80% cut point was used to determine good and poor status. A one-way analysis of variance (ANOVA) and a paired t-test were conducted to assess the relationship between KAP scores and the socio-demographic factors of the respondents. Binary logistic regression analyses were conducted to assess the association between the explanatory variables (i.e., socio-demographic factors and knowledge status) and dependent variables (i.e., KAP status, attitude, and practice variables). Our assumption was that these explanatory variables would have an influence on the dependent variables in this study. Researchers [21,24,28,42,43] reported that socio-demographic variables, including gender, age, education, area of studies, occupation, household size, and income, have significant associations with plastic use (practice), recycling (attitude), and knowledge about plastic pollution. The coding for binary regression was 1 for "yes" or the correct answer and 0 for "no," "maybe", "sometimes", or wrong answer. The odds ratio (OR) with a 95% confidence interval (CI) was used to assess the strength of the association with $p < 0.05$. The Omnibus Tests of Model Coefficients were used for testing the goodness of fit of the binary logistic regression models.

3. Results

3.1. Socio-Demographic Characteristics of Respondents

Among the 302 responses, there were only nine non-Malaysians, and we excluded them from the data analysis due to the low numbers. As a result, the total number of respondents was 294 in the end. Females were dominant (72.4%) in the survey, and the majority of the respondents (75.5%) belonged to the 18–30-year age range (Table 1). More than 75% of the respondents had university-level education and were students by occupation (60.2%). The dominance of younger ages (18–30 years), university-level education, and students as respondents revealed that they were active on social media and willing to volunteer in online surveys. A total of 17% of respondents had a university education in an environmental field.

Table 1. Socio-demographic distribution of respondents.

Variable	Frequency (*N* = 294)	Percentage (%)
Gender		
Male	81	27.6
Female	213	72.4
Age range (years)		
18–30	222	75.5
31–45	37	12.6
Above 46	35	11.9
Highest education level		
Up to secondary schooling	21	7.1
Pre-university	50	17.0
University (Environment related subjects)	50	17.0
University (Non-environment related subjects)	173	58.8
Occupation		
Jobs in government and private sectors	63	21.4
Professional	17	5.8
Students	177	60.2
Others (business, homemaker, retired &unemployed)	37	12.6

3.2. Assessment of KAP Responses

The majority of the respondents were aware that plastic pollution could affect the environment and human health at every stage of its lifecycle (94.2%), as well as the negative impact of incineration of plastic waste (95.6%) (Table S2). However, more than 50% of the respondents were not aware that discarded plastic causes harmful effects on organisms, plastic can degrade into plastic fragments, and microplastics can be inhaled through the air. On the attitude side (see Table S3), most of the respondents agreed that plastic pollution is the biggest environmental problem (84.4%), that plastic pollution is severe in Malaysia (86.4%), that the public has the responsibility for reducing plastic pollution in Malaysia (90.8%), that an increase in the public's awareness can help in mitigating plastic pollution (86.4%), that littering or mismanagement of plastic wastes can cause plastic pollution (92.9%), and that plastic that ends up in landfills or the ocean can harm human health and the environment (92.5%). However, the respondents' level of plastic use and pollution reduction practices differed from their attitudes. Only one-third of respondents (33.3%) stated to separate plastic waste from other household waste; 49% of respondents do not or sometimes recycle plastic waste, around 30% of them use reusable bags for shopping, and 89% of respondents purchase plastic-made products (Table S4).

3.3. Respondents' KAPScores towards Plastic Pollution

The findings of this study show that respondents had poor average knowledge scores (95% CI 3.88–10.94, on a scale of 11) and practice scores (95% CI 1.09–6.53, on a scale of 6) across all socio-demographic groups (Table 2). The average knowledge score of environmental-related university students (95% CI 4.32–11.84) was significantly higher than that of other educational groups ($p < 0.01$). This reveals that respondents who had environmental education at the tertiary level enhanced their knowledge of plastic pollution. There were no effects of socio-demographic characteristics on attitudes and practices, as these scores were not significantly different across socio-demographic groups.

Table 2. Socio-demographic distribution of the respondents and their KAP scores.

Variable		Knowledge Score (95% CI)	*t*/*F* Test	*p*-Value	Attitude Score (95% CI)	*t*/*F* Test	*p*-Value	Practice Score (95% CI)	*t*/*F* Test	*p*-Value
Overall (mean)		3.88, 10.94			5.98, 10.92			1.09, 6.53		
Gender	Male	4.09, 10.95	0.641	0.522	5.74, 11.18	−0.27	0.522	0.68, 6.68	−0.80	0.424
	Female	3.77, 10.95			6.33, 10.61			1.21, 6.43		
Age	18–30	3.78, 10.88	0.70	0.381	6.30, 10.62	0.62	0.539	1.03, 6.41	2.64	0.073
	31–45	4.55, 11.01			6.32, 10.94			1.66, 6.88		
	Above46	3.57, 11.37			5.19, 11.47			0.85, 6.53		
Education	Up to Secondary	3.65, 9.93	4.03	0.008	5.47, 10.91	1.80	0.147	1.45, 6.07	0.81	0.491
	Pre-University	3.21, 10.81			5.27, 11.31			1.51, 6.33		
	University (Environment)	4.32, 11.84			7.07, 10.45			1.44, 6.54		
	University (Non-Environment)	4.05, 10.75			6.31, 10.63			0.81, 6.57		
Occupation	Jobs in government & private sectors	3.57, 11.21	0.50	0.684	5.57, 11.01	2.10	0.101	0.95, 6.55	0.51	0.679
	Professional	4.26, 11.08			6.22, 11.36			0.29, 6.83		
	Student	3.95, 10.97			6.60, 10.52			1.14, 6.40		
	Others	3.72, 10.5			5.32, 11.00			1.25, 6.77		

Furthermore, Table 3 shows that 28.9% of the respondents belonged to the "poor knowledge with poor attitude" group and 65.3% to the "poor knowledge with poor practice" group. Only 27.2% of the respondents demonstrated good knowledge, while 19.4% had good attitudes, and 7.5% showed good practices. Among the respondents with good knowledge, 7.8% exhibited poor attitudes, and 19.7% demonstrated poor practices. These results show that among those respondents with "good knowledge," many of them exhibit poor attitudes and practices.

Table 3. Cross tabulation of good and poor attitudes and practices with respect to the participants' plastic pollution knowledge status.

		Knowledge (*n*) (%)	
		Good	**Poor**
		80 (27.2)	**214 (72.8)**
Attitudes	Good (*n*) (column %) (% of total)	57 (71.2) (19.4)	129 (60.3) (43.9)
	Poor (*n*) (column %) (% of total)	23 (28.8) (7.8)	85 (39.7) (28.9)
Practices	Good (*n*) (column %) (% of total)	22 (27.5) (7.5)	22 (10.3) (7.5)
	Poor (*n*) (column %) (% of total)	58 (72.5) (19.7)	192 (89.7) (65.3)

3.4. Socio-Demographic Factors Associated with KAP Scores

Elder respondents (above 46 years) possessed significantly ($p < 0.01$) higher knowledge of plastic pollution (by a 4.304 factor) compared to younger respondents (18–30 years) (Table 4). The reason might be due to the long-life experiences of older respondents, so they are more aware of the current plastic pollution situation. Respondents between the ages of 31 and 45 reported significantly ($p < 0.01$) higher attitudes (OR 4.019; $p < 0.05$) and practices (OR 4.056; $p < 0.05$) than respondents between the ages of 18 and 30. This may be due to their higher level of acceptance of plastic pollution-related measures. Compared to respondents with secondary education, respondents with environmentally related university education had a higher likelihood of knowing about plastic pollution (OR 10.343; $p < 0.01$). This indicates that respondents with environmental-related education have more knowledge of plastic pollution because they have a pollution-related curriculum in their study programs. On the other hand, respondents (retired, homemakers, unemployed, and business owners) demonstrated significantly higher practice status (OR 5.25; $p < 0.05$) compared to that of students, professionals, and government and private sector employees.

Table 4. Binary logistic regression of the KAP scores with different socio-demographic variables of the respondents (values are odds ratio followed by 95% confidence interval in parenthesis).

Variable		**OR (95% CI)**		
		Knowledge	**Attitude**	**Practice**
Gender	Male	1.00 (reference)	1.00 (reference)	1.00 (reference)
	Female	0.960 (0.495–1.863)	1.086 (0.598–1.974)	0.673 (0.309–1.465)
Age	18–30	1.00 (reference)	1.00 (reference)	1.00 (reference)
	31–45	2.051 (0.719–5.850)	4.019 ** (1.495–10.807)	4.056 * (1.145–14.364)
	Above 46	4.304 ** (1.451–12.766)	2.316 (0.895–5.993)	1.416 (0.346–5.797)
Education	Up to Secondary	1.00 (reference)	1.00 (reference)	1.00 (reference)
	Pre-University	2.509 (0.471–13.353)	0.698 (0.221–2.202)	1.811 (0.306–10.734)
	University (Environment)	10.343 ** (1.992–53.690)	1.352 (0.402–4.551)	3.835 (0.648–22.693)
	University (Non-Environment)	4.110 (0.866–19.509)	0.679 (0.237–1.951)	3.017 (0.585–15.572)
Occupation	Jobs in government & private sectors	1.00 (reference)	1.00 (reference)	1.00 (reference)
	Professional	2.031 (0.619–6.661)	1.363 (0.415–4.481)	1.896 (0.395–9.101)
	Student	1.791 (0.708–4.531)	2.026 (0.944–4.351)	3.743 (0.982–14.256)
	Others	0.811 (0.280–2.351)	1.056 (0.425–2.625)	5.262 * (1.473–18.794)

* Significant at 0.05 level; ** Significant at 0.01 level.

3.5. Association between Attitude with Socio-Demographic Factors and Knowledge Status

Respondents aged between 31 and 46 years showed higher agreement (by a 2.75 factor) in banning the use of single-use plastics in Malaysia (OR 2.75; $p < 0.05$), and they were more confident in stopping the use of single-use plastics in their daily lives (OR 7.43; $p < 0.01$) than the respondents in other age categories (Table 5). Respondents with environmental-related university education (OR 7.46; $p < 0.05$), pre-university education (OR 5.15; $p < 0.05$)) and non-environmental university education (OR 4.31; $p < 0.05$) showed higher odds of stopping the use of single-use plastics in their daily lives than respondents with up to secondary level education. This shows that education is an important factor in improving plastic pollution-related attitudes among people. This was further confirmed when students reported higher odds in favour of banning the use of single-use plastics in Malaysia (OR 2.37; $p < 0.05$). On the other hand, professionals showed significantly higher agreement

that taxation on single-use plastics is an appropriate action towards reducing plastic use (OR 3.41; $p < 0.05$). Respondents with good knowledge reported significantly higher odds that plastic pollution in Malaysia is severe (OR 8.08; $p < 0.05$) and that plastic waste ending up in landfills can harm the environment and human health (OR 4.71; $p < 0.05$).

3.6. Association between Practice with Socio-Demographic Factors and Knowledge Status

In comparison to younger ones (18–30 years), respondents aged 31–45 years were highly willing to separate plastic waste from their household waste (OR 4.39; $p < 0.05$), recycle plastic waste (OR 4.16; $p < 0.05$), use reusable bags for grocery shopping (OR 4.75; $p < 0.05$) and participate in plastic pollution related awareness campaigns (OR 6.25; $p < 0.05$) (Table 6). Respondents with an environmental-related university education were more likely to use reusable shopping bags (OR 3.65; $p < 0.05$). Furthermore, students were more likely to bring reusable shopping bags (OR 3.39; $p < 0.05$). On the other hand, professionals reported higher odds of purchasing plastic products (OR 6.78; $p < 0.05$). In some instances, respondents' knowledge is positively associated with good practices. For example, respondents with good knowledge showed higher odds of recycling plastic waste (OR 1.75; $p < 0.05$) and lower odds of purchasing plastic-made products (OR 0.24; $p < 0.05$) than those with poor knowledge.

Table 5. Binary logistic regression of different variables of attitude with socio-demographic variables and knowledge status (values are odds ratio followed by 95% confidence interval in parenthesis).

Explanatory Variable(s)	Plastic Pollution as Biggest Problems	Severeness of Plastic Pollution in Malaysia	Government Action in Reducing Plastic Pollution	Public Responsibility	Public's Awareness	Littering or Causes of Plastic Pollution	Taxation on Single-Use Plastics	Banning the Use of Singles-Use Plastics	Plastics in Landfills Can Harm Human Health	Stop the Use of Single-Use Plastic in Daily Life
Gender										
Male (ref)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Female	1.98 (0.95–4.13)	0.90 (0.38–2.10)	0.69 (0.35–1.36)	0.58 (0.20–1.68)	1.37 (0.62–3.03)	1.54 (0.54–4.35)	1.11 (0.62–1.99)	0.63 (0.35–1.13)	0.57 (1.67–1.92)	0.35 (0.19–0.67)
Age range (years)										
18–30 (ref)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
31–45	2.15 (0.65–1.13)	1.82 (0.46–7.12)	0.84 (0.29–2.38)	1.79 (0.38–8.52)	1.25 (0.38–4.04)	1.42 (0.31–6.57)	1.50 (0.61–3.72)	2.75 (1.11–6.86) *	3.02 (0.30–30.76)	7.43 (2.56–21.53) **
Above 46	0.91 (0.30–2.72)	0.73 (0.20–2.75)	0.70 (0.24–2.06)	2.40 (0.47–12.16)	2.37 (0.61–9.18)	2.0 (0.4–10.10)	1.62 (0.63–4.21)	1.54 (0.60–3.97)	0.52 (0.11–2.52)	1.98 (0.74–21.53)
Highest education level										
Up to secondary (ref)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Pre-university	0.71 (0.15–3.30)	1.41 (0.37–5.43)	1.87 (0.60–5.84)	1.89 (0.44–8.17)	1.21 (0.29–5.01)	0.45 (0.08–2.67)	1.12 (0.38–3.27)	1.12 (0.38–3.30)	1.31 (0.25–6.76)	5.15 (1.54–17.21) *
University (Environment)	0.54 (0.11–2.70)	3.33 (0.61–18.08)	1.41 (0.43–4.64)	6.06 (0.87–42.43)	1.02 (0.23–4.53)	0.60 (0.08–4.41)	1.67 (0.53–5.24)	1.57 (0.51–4.87)	0.88 (0.14–5.43)	7.46 (2.09–26.65) *
University (Non-environment)	0.55 (0.14–2.21)	2.02 (0.59–7.01)	1.66 (0.60–4.62)	2.91 (0.74–11.38)	1.21 (0.34–4.31)	1.34 (0.23–7.77)	1.38 (0.52–3.68)	1.17 (0.44–3.13)	2.82 (0.56–14.12)	4.31 (1.40–13.32) *
Occupation										
Jobs in government & private sectors (ref)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Professional	1.83 (0.43–7.70)	0.60 (0.13–2.86)	1.80 (0.36–9.10)	0.87 (0.08–8.97)	3.36 (0.39–29.22)	1.43 (0.14–14.34)	3.41 (0.97–12.04) *	1.81 (0.58–5.63)	5.570E7 (0.01–0.001)	1.63 (0.45–5.84)
Student	2.41 (0.96–6.11)	1.32 (0.46–3.78)	0.72 (0.30–1.73)	0.99 (0.26–3.75)	1.59 (0.59–4.33)	2.17 (0.56–8.36)	2.67 (1.25–5.72)	2.37 (1.09–5.19) *	1.15 (0.27–4.80)	2.12 (0.94–4.79)
Others	1.39 (0.47–4.10)	1.64 (0.46–5.91)	0.71 (0.27–1.86)	0.29 (0.07–1.19)	0.58 (0.19–1.75)	0.53 (0.13–2.08)	0.94 (0.39–2.23)	1.68 (0.69–4.07)	0.53 (0.12–2.31)	1.22 (0.48–3.13)
Knowledge score										
Poor (ref)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Good	1.31 (0.60–2.84)	8.08 (1.86–35.18) *	1.86 (0.96–3.60)	1.80 (0.58–0.60)	1.23 (0.54–2.82)	2.10 (0.57–7.74)	1.27 (0.72–2.24)	0.92 (0.54–1.59)	4.71 (1.00–22.15) *	1.12 (0.64–1.99)
Nagelkerke's R^2	0.067	0.135	0.046	0.096	0.044	0.100	0.07	0.05	0.145	0.156
-2Log likelihood	243.43	211.16	332.77	167.18	226.70	139.29	377.05	396.15	138.19	370.76
Chi-square	11.62	22.70	9.43	13.20	7.16	12.01	15.58	11.29	18.19	36.47
p-value	0.39	0.01	0.58	0.28	0.78	0.36	0.15	0.41	0.07	0.00

* Significant at 0.05 level; ** Significant at 0.01 level.

Table 6. Binary logistic regression of different variables of practice with socio-demographic variable and knowledge status (values are odd ratio followed by 95% confidence interval in parenthesis).

Explanatory Variable	Separation of Plastic Waste	Recycling of Plastic Waste	Reusable Bag(s) in Shopping	Reusable Container(s) in Takeaways	Frequent Purchase of Plastic Products	Participation in Campaigns
Gender						
Male (ref)	1.00	1.00	1.00	1.00	1.00	1.00
Female	1.01 (0.55–1.87)	1.42 (0.79–2.57)	0.85 (0.45–1.60)	0.59 (0.33–1.06)	1.69 (0.64–4.52)	1.27 (0.60–2.69)
Age range (years)						
18–30 (ref)						
31–45	4.39 (1.67–11.55) *	4.16 (1.60–10.82) *	4.75 (1.70–13.30) *	1.28 (0.52–3.11)	0.88 (0.24–3.30)	6.25 (1.81–21.51) *
Above 46	1.77 (0.62–5.01)	2.49 (0.95–6.54)	1.80 (0.67–4.80)	1.02 (0.40–2.60)	0.27 (0.05–1.58)	1.94 (0.45–8.34)
Highest education level						
Up to secondary (ref)	1.00	1.00	1.00	1.00	1.00	1.00
Pre-university	1.03 (0.33–3.26)	1.34 (0.45–4.01)	1.42 (0.46–4.40)	1.11 (0.38–3.27)	0.93 (0.19–4.49)	1.87 (0.43–8.13)
University (Environment)	1.19 (0.36–3.93)	1.34 (0.43–4.24)	3.65 (1.03–12.96) *	1.58 (0.51–4.87)	0.48 (0.08–2.86)	1.02 (0.22–4.79)
University (Non-environment)	1.13 (0.40–3.20)	1.85 (0.68–5.06)	1.47 (0.53–4.14)	1.80 (0.67–4.84)	0.69 (0.15–3.06)	1.41 (0.36–5.51)
Occupation						
Jobs in government & private sectors (ref)	1.00	1.00	1.00	1.00	1.00	1.00
Professional	1.43 (0.44–4.70)	1.30 (0.39–4.34)	0.49 (0.15–1.62)	0.44 (0.14–1.39)	6.78 (1.31–34.99) *	1.25 (0.31–5.12)
Student	1.96 (0.81–4.73)	1.67 (0.78–3.66)	3.39 (1.52–7.53) *	1.13 (0.53–2.38)	1.25 (0.34–4.53)	2.75 (0.83–9.09)
Others	1.36 (0.53–3.51)	1.48 (0.60–3.67)	2.18 (0.83–5.68)	1.51 (0.63–3.64)	3.58 (0.88–14.64)	0.77 (0.22–2.68)
Knowledge score						
Poor (ref)	1.00	1.00	1.00	1.00	1.00	1.00
Good	1.64 (0.93–2.87)	1.75 (1.00–3.06) *	1.67 (0.88–3.16)	1.43 (0.83–2.47)	0.24 (0.07–0.86) *	1.71 (0.89–3.29)
Nagelkerke's R^2	0.067	0.089	0.131	0.046	0.133	0.082
-2Log likelihood	359.73	387.05	341.06	396.35	193.63	276.37
Chi-square	14.54	20.30	28.92	10.35	20.99	15.64
p-value	0.20	0.04	0.002	0.49	0.03	0.15

* Significant at 0.05 level.

4. Discussion

4.1. KAP Scores

Results show that respondents have relatively low average knowledge scores, high average attitude scores, and low average practice scores across all socio-demographic groups. Elderly respondents have shown higher odds of plastic pollution-related knowledge. It shows that respondents with higher educational levels, especially those who took environmental-related subjects, have a higher knowledge status. Besides that, respondents aged between 31–45 years have significantly higher odds of attitudes (OR4.019) and practices (OR4.056) among the age groups. This suggests that millennials are more socially conscious as they grew up with the internet and social media, are more open-minded and optimistic and are more conscious about the environment and their health [44]. Respondents that studied environmental-related subjects had a better understanding of plastic pollution as they demonstrated higher odds (OR10.343). Environmental education, involving projects and other actions, is considered an important way to mitigate environmental problems, such as plastic pollution [42]. Research reported that the respondents with higher educational levels have higher knowledge of plastic pollution [42]. Age and education are considered common predictors for both knowledge and environmentally significant behaviour [45]. Higher-educated people value scientific knowledge as an important source of information, and so their involvement in citizen science programs might be an effective intervention strategy for motivating others to reduce plastic pollution [42].

4.2. Attitude, Practices, and Associated Socio-Demographic Factors

Most of the respondents have a positive attitude toward reducing plastic pollution in Malaysia. Single-use plastic is a major source of plastic pollution in Malaysia [15]. Respondents aged between 31 and 46 years have shown higher odds (OR 2.75) towards banning single-use plastics in Malaysia, and they are optimistic (OR 7.43) about stopping using these in their daily lives. In a study in Europe, Filho et al. [21] found that respondents between the ages of 18–25 and 36–45 were among those choosing products with less plastic. Zen et al. [37] observed that consumers are more supportive of banning plastic bags in supermarkets, shopping malls, and retailers, but not its extension to traditional or public

markets, night markets, or morning markets. However, consumers' behaviour toward using less plastic also depends on the availability of alternatives, price, time, convenience, habits, reachability, and so on [46]. Respondents with higher levels of education have also shown higher odds of stopping single-use plastics. Filho et al. [21] reported that factors like educational background and age play a significant role in the level of engagement to reduce plastic usage and the actions undertaken. Any interventions aimed at reducing single-use plastics need to consider these factors.

Like attitude, 31–46-year-old respondents are significantly and highly (by 4–6 factors) willing to separate, recycle, and reuse plastic bags and join in an awareness creation program on plastic pollution. Students and respondents with education in environmental disciplines have shown significantly higher odds with regard to the use of reusable plastic bags. Filho et al. [21] also reported similar findings. Afroz et al. [16] reported that people have a positive attitude towards recycling but are less motivated to recycle. The practice of recycling itself is controlled by many factors, such as convenience, social norms, moral consideration, environmental awareness, and knowledge, regardless of educational level, gender, income, or age [36]. Environmental education in daily school scenarios can allow students to connect with environmental issues and develop positive attitudes, knowledge, and motivation to act [47].

Respondents' good knowledge status is reflected in some of the attitudes and practices towards plastic pollution, which indicate that respondents' knowledge can influence their attitudes and practices. Respondents with good knowledge were more concerned about the severity of plastic pollution in Malaysia (OR 8.08) and the harmful effects of plastic waste that ended up in landfills (OR 4.71). They have reported recycling plastic waste (OR 1.75) and purchasing fewer plastic products (OR 0.24). According to De Pretto et al. [48], knowledgeable people are more concerned about environmental pollution and engage in protective behaviours.

4.3. Implications

Single-use plastics are responsible for a large part of the overconsumption, mismanagement, and pollution problems in Malaysia [49] and probably elsewhere as well. This study also confirmed that single-use plastics are important environmental problems, and respondents showed their willingness to reduce their consumption of these plastic products. The Malaysian government recognizes the severity of the single-use plastics problem and has implemented interventions such as prohibiting free plastic bags in grocery stores and supermarkets and imposing a 0.20 Malaysian Ringgit per bag levy, which has resulted in some positive outcomes (e.g., raising people's awareness) [15,16,37]. The government has also developed and been implementing the "Roadmap Towards Zero Single-use Plastics 2018–2030" [50]. This phased, evidence-based, and participatory roadmap aimed to adopt an environmentally sound integrated policy framework towards ending single-use plastics by 2030. According to a newspaper report, even though several state governments banned the use of single-use plastic straws in 2019 in accordance with the Roadmap 2018-30, it was not working effectively [51], most likely due to a lack of awareness of the plastic problem, a lack of suitable alternatives, and a lack of citizen participation in the development and implementation of interventions. Findings from this study also indicate that most of the respondents lack knowledge of plastic pollution, so they exhibit poor practices as well, even though they have a relatively higher attitude. The government needs to invest more in citizen science-related programs aimed at improving peoples' knowledge and the development of eco-friendly, affordable, and readily available food packaging materials (e.g., bioplastics).

5. Study Limitations

One of the limitations of this study is that the number of respondents was not enough to represent the whole study area, Malaysia. According to Morse [52], at least 400 responses are needed with a $\pm$5% margin of error for a population size greater than 100,000. Even

though the questionnaire was reviewed by experts and pre-tested, some questions seem unclear and confusing, so respondents might be biased in answering those questions. Since only English was used in the questionnaire, responses from different races or local communities could not be recorded. A future study should also consider additional factors such as the respondent's living area (rural or urban), income, nature-connectedness, and membership in nature clubs or associations to perform a more comprehensive analysis of different aspects. Besides that, respondents in this study were mostly students or younger generations, which may not represent the overall demography of Malaysia. Physical interviews with targeted respondents might be useful to minimize this limitation.

6. Conclusions

This study provides a general understanding of respondents' KAP towards plastic pollution in Malaysia. The findings could serve as a baseline for authorities to develop guidelines or strategies for reducing plastic pollution in the country. Results showed that most of the respondents had poor knowledge and practiced towards plastic pollution but relatively higher attitudes, with some significant influence of the socio-demographic factors on the KAP scores, such as age, education, and occupation. To convert good attitudes into practices, authorities may undertake interventions such as environmental awareness creation, incorporating plastic pollution topics into formal and informal education, and providing recycling facilities in nearby localities. Authorities may also provide incentives (e.g., nominal cash vouchers) to encourage residents' pro-environmental behaviours, such as recycling and avoiding single-use plastic materials.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15021164/s1, Table S1. Social-demographic information, knowledge, attitude and practice-related questions towards plastic pollution. Table S2. Frequency distribution of respondents' responses to knowledge-related questions towards plastic pollution. Table S3. Frequency distribution of respondents' responses on attitude-related questions towards plastic pollution. Table S4. Frequency distribution of respondents' responses to practice-related questions towards plastic pollution.

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Informed Consent Statement: Respondents' online consent was ensured with the following statement: "I read the brief information on study objectives and provided my consent to participate in the survey."

Data Availability Statement: The data presented in this study are available in this article.

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Knowledge, Attitudes, and Practices towards Single-Use Plastic Bags in the United Arab Emirates

Shahad M. Alteneiji [1], Betty T. Mathew [1], Hafsa A. Mohammed [1], Abdelghafar M. Abu-Elsaoud [2,3], Khaled A. El-Tarabily [1] and Seham M. Al Raish [1,*]

[1] Department of Biology, College of Science, United Arab Emirates University, Al Ain 15551, United Arab Emirates; 202004515@uaeu.ac.ae (S.M.A.); betty_m@uaeu.ac.ae (B.T.M.); 201912140@uaeu.ac.ae (H.A.M.); ktarabily@uaeu.ac.ae (K.A.E.-T.)
[2] Department of Biology, College of Science, Imam Mohammad Ibn Saud Islamic University (IMSIU), Riyadh 11623, Saudi Arabia; amsmohamed@imamu.edu.sa
[3] Department of Botany and Microbiology, Faculty of Science, Suez Canal University, Ismailia 41522, Egypt
* Correspondence: seham.alraish@uaeu.ac.ae

Abstract: Due to their widespread misuse and inadequate waste management, single-use plastic bags represent the global plastic pollution crisis and ecosystem degradation. Comprehensive research on population knowledge, attitudes, and practices (KAP) regarding single-use plastic bags is lacking in the United Arab Emirates (UAE). This study aims to fill this gap by assessing the KAP levels among the UAE population and determining the relationships between these variables. A five-point Likert scale questionnaire from previous studies was used in a cross-sectional study, and the questionnaire was distributed via Google Forms. The UAE University Research Ethics Committee approved the study (ERSC_2024_4377). Non-probability sampling and G*power statistical analysis version 3.1.9.6 determined 385 UAE residents aged 18 years and older. The findings were verified through face-to-face interviews and Cronbach's alpha tests. KAP variable associations were assessed using Chi-square tests, Pearson's correlation coefficients, and a structural equation model with SPSS version 29.0. This test was chosen for robust categorical and continuous data. The study included 84.7% female, and 15.3% male participants aged 18 to 65 years, primarily aged 18 to 25 years, with most holding bachelor's degrees (47.6%), and were students (51.4%), employed (33.1%), or unemployed (12.2%). The results indicated a favourable inclination towards sustainability, with mean ± standard deviation (SD) for seven knowledge questions (3.89 ± 0.7), seven attitude questions (3.99 ± 0.7), and five practice questions (3.42 ± 0.8) exceeding the midpoint. The correlation test showed that total knowledge was positively correlated with practice (r = 0.399; $p < 0.001$) indicating the increasing knowledge regarding single-use plastic bags associated with increasing sustainable practices and attitudes (r = 0.648; $p < 0.001$). There was also a significant correlation between the total attitude and practice (r = 0.487; $p < 0.001$). The findings suggest targeted educational and policy interventions to promote sustainable behaviour.

Keywords: consumer behaviour; environmental awareness; environmental education; environmental impact; plastic pollution; plastic waste reduction; public perception; recycling; sustainability; waste management

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1. Introduction

A single-use plastic bag is a plastic bag specifically intended for one-time use [1,2]. The widespread use of disposable plastic bags can be mainly attributed to their affordable cost, lightweight design, and long-lasting nature, making them a popular choice for various consumer activities, especially grocery shopping [1–4]. However, misuse of plastic bags, including excessive consumption and improper disposal, significantly contributes to plastic pollution [3]. This pollution has dangerous environmental effects on terrestrial and aquatic

ecosystems [5–13]. The mismanagement of single-use plastic bags disposal can be attributed to insufficient waste management systems, which include garbage disposal, recycling, and energy generation from wastes [9]. The misuse may also be linked to a lack of awareness regarding the harmful consequences of inappropriate plastic use on the environment and resources [10–13]. Every year, the world uses and disposes of around five hundred billion plastic bags, meaning that one million bags are thrown away every minute [14–16].

Plastic bags that are discarded in aquatic ecosystems have the potential to accumulate in rivers and oceans [14]. This phenomenon disrupts the ecological balance and causes the degradation of habitats for diverse marine species [15–17]. In addition, numerous marine organisms, including seabirds, frequently consume plastic bags due to the incorrect perception that they are edible [16,17]. Consuming these discarded plastic bags can result in substantial internal harm and mortality [18–20]. Single-use plastic bags, despite their convenience and widespread use in terrestrial ecosystems, pose a substantial ecological risk due to their slow decomposition and long-lasting presence in the land [21,22].

Plastic products' extensive utilization and prevalence have raised concerns regarding the exhaustion of non-renewable resources, leading to the inefficient utilization of energy and raw materials [23,24]. Plastic materials can experience long-lasting environmental degradation spanning thousands of years [25]. The improper disposal of single-use plastic bags can also cause infrastructure damage by obstructing drainage systems [26,27]. The accumulation of wastes hinders the natural movement of water, which in turn raises the likelihood of flooding and poses threats to public health [26–28].

Conducting knowledge (information), attitudes (feeling), and practices (behaviour) (KAP) studies is crucial for gathering data on individuals' KAP regarding specific subjects [29]. These studies are essential for identifying gaps in the target KAP population, and they provide valuable insights that can inform on the development of effective strategies for environmental management [28,29]. Acquiring a thorough comprehension of these factors is essential for developing focused tactics that encourage sustainable behaviours and improve environmental consequences [27,29].

Sustainability refers to the capacity to maintain or sustain a process over time, ensuring its continuity for both the current and future generations [30]. Research focused on sustainability KAP can aid in achieving the objective of environmental sustainability [31]. On the other hand, effective resource and waste management is essential for achieving sustainability, particularly when addressing issues such as plastic pollution [31]. SDG 12 prioritizes sustainable consumption and production, promoting the responsible use and disposal of single-use plastics to safeguard the environment [32].

Furthermore, SDG 14 specifically addresses life below water and emphasizes the significance of effectively managing single-use plastic bags to mitigate their detrimental effects on marine ecosystems [33,34]. These objectives are in line with current efforts to address marine pollution and promote environmental sustainability [24,33,34]. The KAP research conducted on single-use plastic bags has a substantial influence on various studies [33]. The literature review provides a comprehensive examination but lacks an exploration of relevant research on single-use plastic bags in some countries, particularly in the United Arab Emirates (UAE) and the Gulf Cooperation Council (GCC) [35].

Several studies observed the gaps in the KAP of some populations, such as the participants in Durban, South Africa. The findings revealed that these participants generally hold negative attitudes towards single-use plastic and have a strong understanding of its negative effects on the environment [36]. They also showed a high level of knowledge regarding the environmental impacts of single-use plastic [36]. Previous research has also investigated various aspects of the utilization of single-use plastic bags, but significant gaps remain. For instance, a study conducted by Abdullah et al. [12] in Malaysia examined the relationship between knowledge and practices only and identified a correlation between them that was limited to certain groups, not to the general population, without examining the attitudes of all of them [12].

While another comprehensive study in Malaysia examined the KAP towards plastic among Malaysians, there is a lack of similar research in the UAE [37]. Separate research conducted in the Klang Valley, Malaysia utilized a self-administered questionnaire to specifically evaluate the KAP related to plastic use and management and its investigation was limited to young individuals and was specifically during the COVID-19 pandemic [38]. A study conducted in Greece by Charitou et al. [23] also focused exclusively on assessing the knowledge and attitudes towards marine plastic pollution. It was noted that the participants lacked a sufficient understanding of marine plastic pollution [23]. Nevertheless, they exhibited a favorable disposition towards diminishing their utilization of plastic [23].

A recent KAP study conducted by Hammami et al. [39] in the UAE with secondary school students in Sharjah, UAE assessed plastic pollution knowledge and attitudes. Four hundred students from six Sharjah secondary schools participated in a cross-sectional study. Self-administered questionnaires were distributed via probability-stratified random sampling in February and April 2016 [39]. The majority of the population understands how harmful plastic waste is to the environment (85.5%). A mean knowledge score of 53% was observed, with females ($p < 0.01$) and students with more educated mothers ($p = 0.014$) exhibiting more pro-environmental behaviours [39]. However, it did not include the wider adult population of the UAE, and its scope was limited to general sustainability without specifically addressing the issue of single-use plastic bag misuse [39].

Another example of a study conducted by Radwan and Khalil [40] in Sharjah is a study that investigated environmental sustainability in general without specifying single-use plastic, and the respondents were only Sharjah University students [40]. Another study performed by Alhosani in the UAE, specifically Ajman, implemented measures aimed at mitigating the plastic pollution issue and aimed to achieve zero emissions and promoted a ban on plastic bags, including the reduction of single-use plastic production [41]. However, they focused only on a specific region [41]. In addition, the previous study mentioned a high carbon footprint from the extensive utilization of plastic bags, with individuals consuming an average of 250 bags annually, reflecting unfavorable practices [41]. This shows the importance of assessing and evaluating the KAP of single-use plastic bags in UAE residences to know the reason behind plastic misuse [41].

Regarding the sociodemographics of the environmental KAP, a study in Malaysia showed a sociocultural correlation between age and knowledge [12]. Similarly, a study conducted in Greece and Lebanon examined the knowledge and attitudes of individuals in high- and upper-middle-income economies regarding the current use of plastics, their recycling practices, and the possibility of replacing them with more sustainable and biodegradable materials [42]. However, the study did not investigate the actual practices of these two populations.

In UAE, there is no study regarding the correlation between sociocultural factors and single-use plastic bags. However, a study by Rajput et al. [43] in the UAE focused on bottled water showed that they preferred the use of bottled water due to social habits [43]. Additionally, a study performed on single-use face mask in the UAE by Ajaj et al. [44] found that correlations with sociodemographic factors, especially gender, age, and educational attainment, affect group decisions about the best face mask to use and the knowledge of face mask disposal [44].

Generally, the research in the UAE focused more on bottled water instead of single-use plastic bags; in one study, they found that the average resident of the UAE used 450 plastic water bottles a year in 2011 [45]. Despite concerted efforts by non-governmental organizations to curtail the usage of plastic water bottles, little progress has been observed, along with a lack of proactive attitudes [46]. The importance of demographic variables, such as education and gender, in influencing environmental attitudes and behaviours cannot be overstated. However, the previous studies only examined specific aspects of KAP; for example, some studies exclusively concentrated on knowledge and practices [46].

Consequently, there is a lack of research on the KAP regarding single use plastic bags that specifically focuses on the UAE. From all these previous studies, it is appropriate to

conduct a KAP model questionnaire that could fill these gaps regarding UAE research gaps, which is our aim. KAP studies can play a vital role in these efforts by providing data that help researchers understand public perceptions and behaviours related to plastic use and disposal. This understanding can guide the development of educational campaigns and policy measures to reduce plastic pollution [44,45]. For instance, a KAP study on single-use plastic bags in the UAE can reveal the level of awareness among the population about the environmental impacts of plastic waste, their attitudes towards using alternatives, and their actual practices in terms of waste disposal [39–46].

The present study emphasizes the significance of evaluating not only the current knowledge and attitudes but also the willingness to adopt sustainable practices. Consequently, our research focuses on investigating the extent of consciousness among UAE residents and their inclination to implement practical actions in order to mitigate plastic pollution. Our study aims to evaluate the KAP related to single-use plastic bags among the UAE population and to analyze the relationship between demographic factors and KAP levels. This objective raises these research questions and hypotheses:

What is the KAP level of single-use plastic bags in the UAE? Is there any correlation among KAP concerning single-use plastic bags in the UAE? Additionally, is there a relationship between sociodemographic characteristics and KAP regarding the usage of single-use plastic bags in the UAE?

The following hypotheses concerning single-use plastic bags in the UAE were formulated:

H0: *There are no impacts of KAP, and sociodemographics on single-use plastic bags in the UAE*;

H1: *There are impacts of KAP, and sociodemographics on single-use plastic bags in the UAE*.

2. Materials and Methods

2.1. Partial Least Squares Structural Equation Modeling (PLS-SEM) Design

PLS-SEM has been used as a popular research method in various disciplines, including knowledge management (KM) [47,48]. PLS-SEM provides an alternative to covariance-based structural equation modeling (SEM), which is deemed more flexible in data requirements, the specification of relationships, and the ability to handle complex models [48].

Given the varying weights of each criterion, utilizing an advanced analysis method such as PLS-SEM allowed us to estimate complex models with multiple constructs, indicator variables, and structural paths without making distributional assumptions about the data. We utilized PLS-SEM in our research to examine the associations between several constructs in the context of the UAE regarding the KAP associated to the utilization of single-use plastic bags.

The dataset comprised responses from 393 individuals, including demographic information (gender, age, education, and employment status) and their responses to 19 questions assessing knowledge (seven items), attitude (seven items), and practices (five items) regarding single-use plastic bags. The data were first cleaned by handling missing values using mean imputation for numerical variables and mode imputation for categorical variables, ensuring completeness and consistency.

The measurement model was defined by associating the constructs with their respective indicators as follows:

- Knowledge (K) was measured by seven indicators (KQ1 to KQ7);
- Attitudes (A) were measured by seven indicators (AQ1 to AQ7);
- Practices (P) were measured by five indicators (PQ1 to PQ5).

Our structural model hypothesized the following:

- Knowledge influences attitudes;
- Attitudes influence practices;
- Knowledge directly influences practices.

The PLS-SEM of KAP toward the single use of plastic bags was generated using Jamovi 2.3.26 software, estimating its reliability and validity (Figure 1A). Partial least square (PLS) was used in the current research in addition to the SEM technique, which is capable of analyzing latent variables, indicators, and measurement errors in real time.

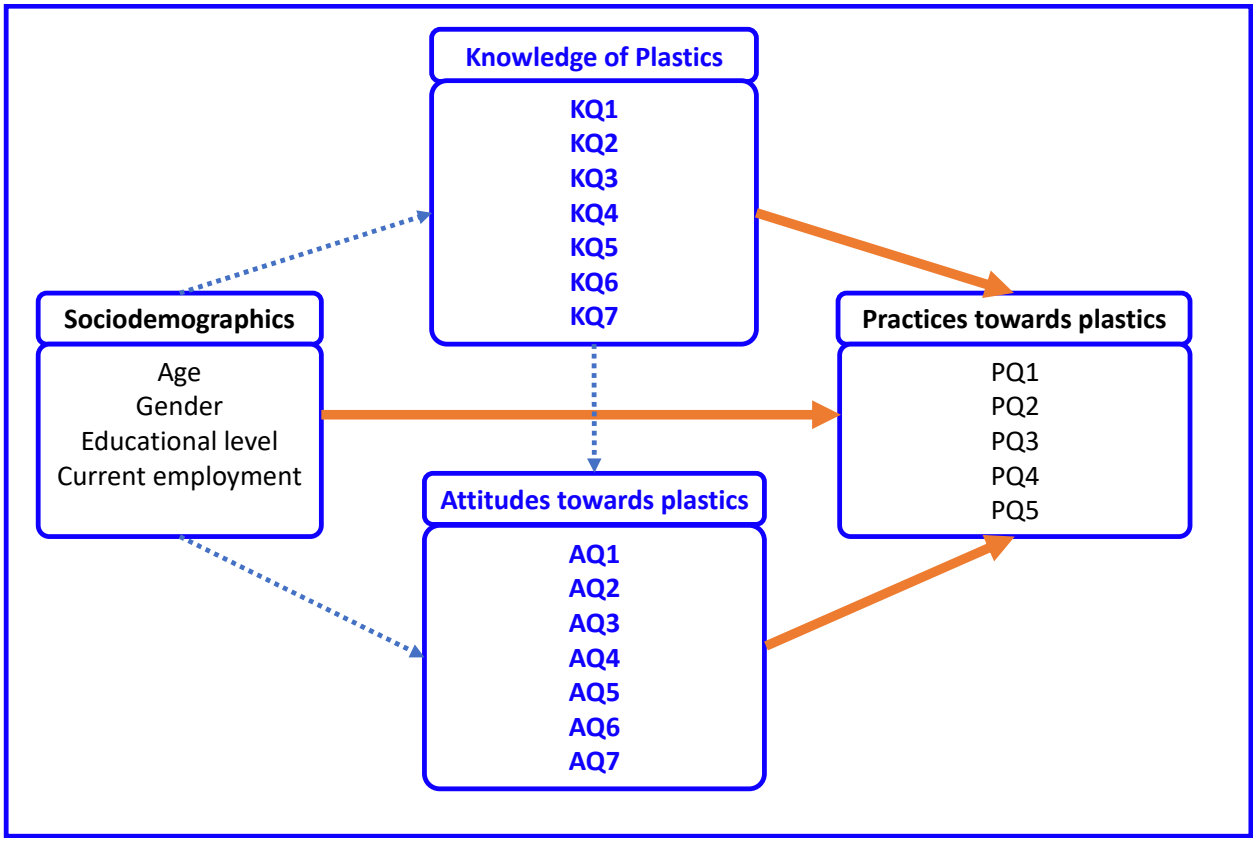


Figure 1. (**A**) Design for partial least squares structural equation modeling (PLS-SEM) including knowledge, attitudes, and practices (KAP). The diagram illustrates the conceptual model for PLS-SEM. It shows the relationships between sociodemographic factors (age, gender, educational level, current employment), knowledge of plastics (KQ1 to KQ7), attitudes towards plastics (AQ1 to AQ7), and practices towards plastics (PQ1 to PQ5). The blue arrows represent the direct influence of sociodemographic factors on the KAP toward plastics, highlighting the initial input factors that potentially affect the respondents' knowledge and attitudes. The orange arrows indicate the hypothesized paths of influence among the core constructs of the model, specifically from knowledge of plastics and attitudes toward plastics to practices toward plastics, emphasizing the direct impacts of knowledge and attitudes on practical behaviors regarding plastic usage. (**B**) Summary of the PLS-SEM process using Jamovi 2.3.26 software. The process involves five key steps: data preparation, project creation, data exploration, theoretical model specification, and model evaluation calculation. Each step is represented by a coloured arrow, illustrating the sequential approach in the PLS-SEM analysis.

The PLS-SEM was used to assess the measurement and structural models in the current study. The measurement model, also known as the outer model, pertains to the connection

between the constructs and their indicators. On the other hand, the structural model focuses on the relationship between the latent constructs themselves. The utilization of PLS-SEM in the present study is attributed to its capability to conduct a concurrent analysis of both the measurement and structural models, thereby yielding more precise computations. The process for calculating PLS-SEM in Jamovi 2.3.26 software is summarised in five stages, as depicted in Figure 1B [47,48].

2.2. Study Design and Data Collection

Data were collected from 427 volunteer participants living in the UAE using a five-point Likert scale items ranging from 1 to 5. A validated online cross-sectional questionnaire was used to assess the KAP of single-use plastic bags in the UAE based on previous articles. Ethical approval was obtained from the Ethical Committee for Research at UAE University (ERSC_2024_4377). The sample for this study was obtained via non-probability sampling and the sample size was calculated based on the number of UAE residents determined using G*power, a tool for computing statistical power analyses (Figure 2) [49–52].

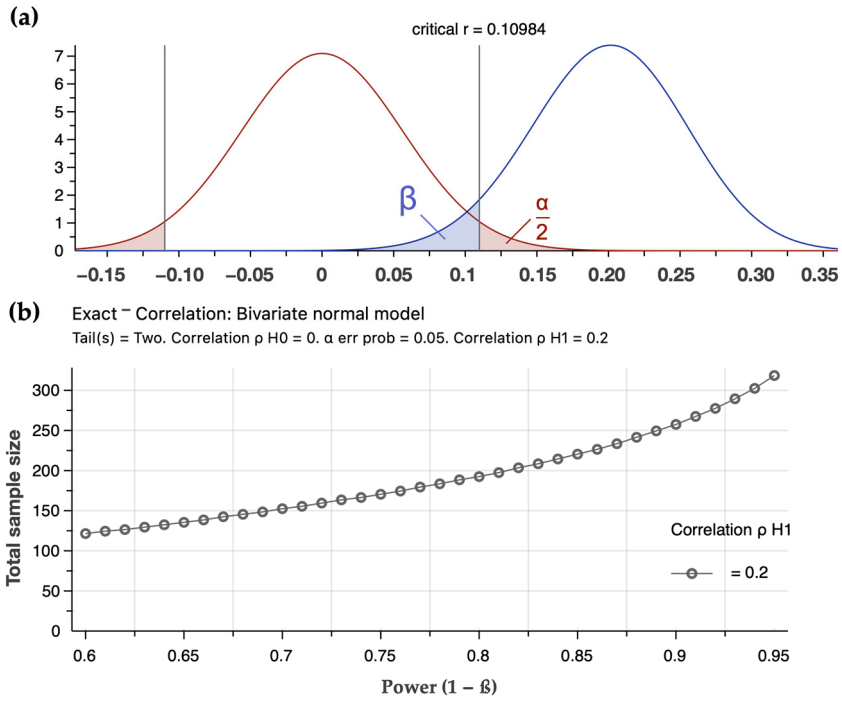


Figure 2. Probability curve for sample size calculations. (**a**) Red curve represents the distribution under the null hypothesis (H0), blue curve represents the distribution under the alternative hypothesis (H1), the critical value is represented by a vertical line labelled with r = 0.10984" which represents the threshold for rejecting the null hypothesis, Alpha (α) = the area under the red curve beyond the critical value represents the significance level (α/2 for a two-tailed test). The shaded area under the blue curve represents β, which is the probability of failing to reject the null hypothesis when the alternative hypothesis is true (Type II error). (**b**) Sample size versus power curve shows the relationship between statistical power (1−β) and the required sample size.

The questionnaire was divided into four parts: sociodemographics, knowledge, attitudes, and practices. Those sections were chosen carefully to evaluate the KAP levels of single-use plastic bags. The sociodemographic questions consisted of seven questions, and the knowledge questions consisted of seven questions, as demonstrated in Table 1 [12,36,53–56]. The attitude questions consisted of seven questions, as demonstrated in Table 2 [12,23,36,53]. Lastly, the practice questions consisted of five questions, as demonstrated in Table 3 [36,53,57,58].

Table 1. Knowledge questions in the questionnaire.

* Knowledge Questions Number	Knowledge Questions (KQ)	Answers
KQ1	I plan to regularly purchase products with eco-sustainable packaging.	Strongly Disagree/Disagree/Neutral/Agree/Strongly agree
KQ2	By reducing my consumption of plastics, I can contribute to the preservation of environmental sustainability.	Strongly Disagree/Disagree/Neutral/Agree/Strongly agree
KQ3	Do you think single-use plastic causes harm to the environment?	No Knowledge/Little Knowledge/Neutral (Undecided)/Medium Knowledge/High Knowledge
KQ4	How serious do you think the harm caused by single-use in the natural environment?	Not severe/mild/moderate/severe/very severe
KQ5	Do you know that plastic bags can take 10–100 years to degrade in landfills?	No Knowledge/Little Knowledge/Neutral (Undecided)/Medium Knowledge/High Knowledge
KQ6	Plastic package contains monomers and additive chemicals.	No Knowledge/Little Knowledge/Neutral (Undecided)/Medium Knowledge/High Knowledge
KQ7	I am aware of the impact plastic litter can have on the environment.	No, not at all/I am a little aware/I am undecided/ I am aware/I am absolutely aware

* KQ1–KQ7 = knowledge question number.

Table 2. Attitude questions in the questionnaire.

* Attitude Question Number	Attitude Questions (AQ)	Answers
AQ1	Would you like to reduce your own consumption of single-use plastic?	No Knowledge/Little Knowledge/Neutral (Undecided)/Medium Knowledge/High Knowledge
AQ2	How many plastic bags do you buy do you buy per week?	I don't know/zero/<5/5–10/>10
AQ3	It's important to avoid single-use plastics bags in our daily life.	Strongly Disagree/Disagree/Neutral/Agree/Strongly agree
AQ4	I am willing to reduce my use of single-use plastic bags.	No I am not willing at all/I am unwilling/I am undecided/I am willing/I am totally willing
AQ5	I am willing to bring my own reusable bag if there is a reward (e.g., a discount on shopping).	No I am not willing at all/I am unwilling/I am undecided/I am willing/I am totally willing
AQ6	I think I am responsible to take care of the environment.	I am not responsible at all/I am a bit responsible/I am moderately responsible/I am quite responsible/I am totally responsible
AQ7	Would you prefer to buy a product that doesn't contain microplastics or isn't made with plastic even if it costs more?	Strongly Disagree/Disagree/Neutral/Agree/Strongly agree

* AQ1–AQ7 = attitude question number.

To ensure a broad representation of views on single-use plastic bags, the inclusion criteria of participants included volunteering and living in the UAE. In addition, participants were between 18 and 80 years old. Exclusion criteria included participants less than 18 years old and visitors to the UAE. The overall Cronbach's alpha coefficient for the KAP questions was 0.824, indicating acceptable internal consistency and the reliability of the study instrument. Before conducting the online survey, face-to-face validation for 55 participants was performed to check the validity of the questionnaire.

Table 3. Practice questions in the questionnaire.

* Practice Question Number	Practice Questions (PQ)	Answer
PQ1	I usually bring my own bag when I go shopping.	Strongly Disagree/Disagree/Neutral/Agree/Strongly agree
PQ2	Do you use reusable shopping bags?	Never/Rarely/Occasionally/Frequently/Very Frequently
PQ3	When you are grocery shopping, do you take your own shopping bags or use ones from the store?	Take own/Use ones from store/Both/It varies/I don't know
PQ4	I think my actions have an impact on the environment.	No, not at all/Yes, they have a small impact/Yes, they have a moderate impact/Yes they have quite an impact/Yes, they have a huge impact
PQ5	I use a new plastic bag every time I go shopping.	Never/Rarely/Occasionally/Frequently/ Very Frequently

* PQ1–PQ5 = practice question number.

2.3. Data Analysis Tools

The statistical analyses were carried out to evaluate and compare knowledge about plastics among participants. Data were collected, checked, revised, and organized in tables and figures using Microsoft Excel 2016. The collected data were subjected to outlier detections, and outliers were detected using boxplot methods and handled using IBM-SPSS. Normality was applied to check the data normality, whether parametric or nonparametric data, using the Shapiro–Wilk test and Kolmogorov–Smirnov test at the $p = 0.05$ level.

The nonparametric data were described statistically using both graphical and numerical descriptions. Parametric data were described in terms of means and standard deviations (SD). Nonparametric data were described in terms of frequencies (n, %), means, medians, modes, quartiles (Q1, Q3), and SD. Inferential statistics of nonparametric data for comparing scores were performed using the Chi-square test for goodness-of-fit.

However, inferential statistics of parametric data for comparing KAP were performed using a one-way analysis of variance (ANOVA) at the $p = 0.05$ level. ANOVA was followed by Duncan's Multiple Range Test (DMRT) at the $p = 0.05$ level. The questionnaire reliability and internal consistency were assessed using Cronbach's alpha test at a probability level of 0.05.

Three significance levels were proposed at $p = 0.05$ (*), 0.01 (**), and 0.001 (***). Data analyses were carried out using the computer software Statistical Package for Social Science (SPSS), IBM-SPSS version 29.0 for Mac OS [59]. The analysis was conducted using the Jamovi 2.3.26 software and the SEM command for linear structural equation modelling. Using the program's default method, ML (maximum likelihood), the analysis followed a two-step approach. The first step tested the measurement model to assess the loadings of indicators on the latent factors, and the second step tested the structural model. Missing data were treated by listwise deletion.

3. Results

3.1. Questionnaire Reliability and Internal Consistency

Cronbach's alpha reliability coefficients for the scale's knowledge (seven questions), attitudes (seven questions), and practices (five questions) were 0.778, 0.802, and 0.753, respectively, indicating high reliability and internal consistency within each scale and for the whole questionnaire. The overall reliability for the combined 19 questions (Table 4) was also high at 0.878. These results suggested that the scales are reliable tools for measuring the constructs of KAP, offering credibility to any findings derived from their use. This high consistency across all scales underscores their suitability for further research and practical applications where these constructs are essential.

Table 4. Reliability analysis.

ID	Scales	Number of Questions	Cronbach's Alpha Reliability *
1	Knowledge	07	0.778
2	Attitudes	07	0.802
3	Practices	05	0.753
Total **		19	0.878

* A Cronbach's alpha reliability value greater than ± 0.70 shows high internal consistency. ** Total of all scale questions.

Table 5 gives a complete reliability and internal consistency analysis for study questions and variables. The table includes the scale mean, scale variance, corrected questions–total correlation, and Cronbach's alpha if the question is deleted. These metrics assess scale question internal consistency.

Table 5. Detailed reliability and internal consistency analysis.

Variable	Scale Means if the Question Deleted	Scale Variance if the Question Deleted	Corrected Questions–Total Correlation	Cronbach's Alpha if the Question Deleted
Age	80.532	145.872	0.229	0.867
Gender	81.550	159.600	0.003	0.861
Education	80.499	153.373	0.267	0.857
Employment	79.870	152.843	0.205	0.860
KQ1 *	79.802	146.762	0.435	0.852
KQ2	79.407	147.849	0.378	0.854
KQ3	79.262	146.587	0.468	0.851
KQ4	79.524	144.821	0.557	0.848
KQ5	79.481	146.414	0.409	0.853
KQ6	79.817	144.043	0.469	0.851
KQ7	79.285	145.097	0.571	0.848
AQ1 **	79.985	143.005	0.523	0.849
AQ2	79.880	143.850	0.515	0.849
AQ3	79.921	146.828	0.390	0.854
AQ4	79.847	142.762	0.530	0.849
AQ5	80.270	151.626	0.259	0.858
AQ6	79.305	144.335	0.596	0.847
AQ7	79.799	152.809	0.216	0.859
PQ1 ***	79.328	144.986	0.552	0.849
PQ2	79.214	145.985	0.654	0.847
PQ3	79.160	146.594	0.539	0.849
PQ4	79.249	143.632	0.604	0.847
PQ5	79.746	143.808	0.537	0.849

* KQ1–KQ7 = knowledge question number 1–7, ** AQ1–AQ7 = attitude question number 1–7, *** PQ1–PQ5 = practice question number 1–5.

Age, gender, education, and employment have good internal consistency, with Cronbach's alpha values of 0.857 to 0.867. These variables have lower corrected questions–total correlations, with gender having a 0.003 correlation, suggesting it may be less aligned with the scale.

KQ1 to KQ7 have moderate to high corrected questions, total correlations between 0.378 and 0.571 and Cronbach's alpha values between 0.848 and 0.854, indicating good internal consistency. AQ1–AQ7 have corrected questions, total correlations from 0.216 to 0.596, and Cronbach's alpha values from 0.847 to 0.859, supporting their internal consistency.

3.2. Normality

The Kolmogorov–Smirnov and Shapiro–Wilk normality tests revealed significant results for the KAP construct reliability.

The Kolmogorov–Smirnov test revealed significant deviations from normality for the constructs of knowledge (D(393) = 0.127, $p < 0.001$), attitudes (D(393) = 0.098, $p < 0.001$), and practices (D(393) = 0.085, $p < 0.001$). Consistently, the Shapiro–Wilk test also indicated significant departures from normality for knowledge (W(393) = 0.950, $p < 0.001$), attitudes (W(393) = 0.945, $p < 0.001$), and practices (W(393) = 0.979, $p < 0.001$).

3.3. Sociodemographic Variables

Four sociodemographic variables existed, and 393 respondents are from the UAE, as shown in Figures 3 and 4.

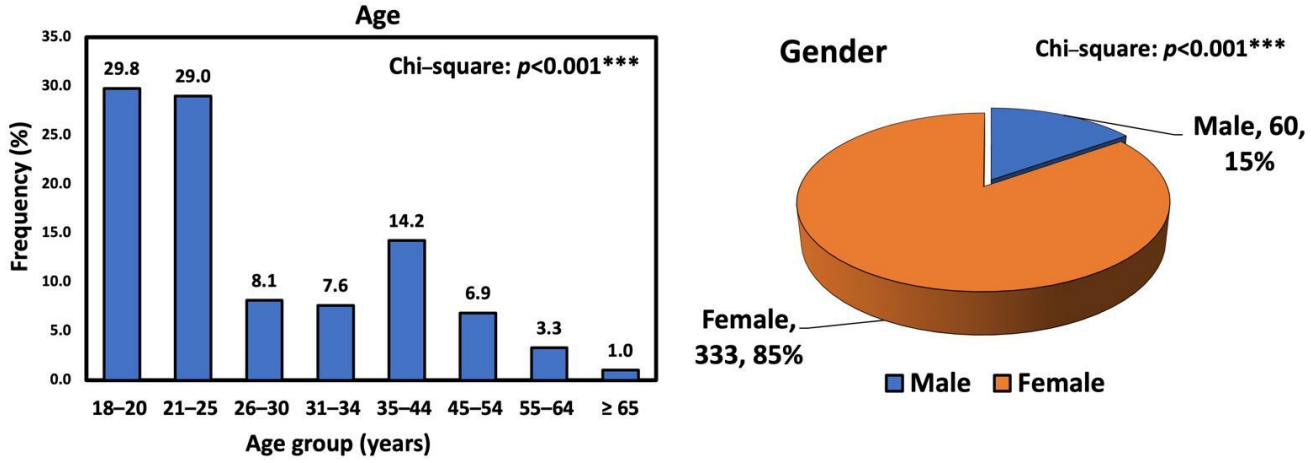


Figure 3. Distribution of responses according to age groups and gender among participants in terms of frequency; n = number of participants in each category; % = frequency percentage from total number of participants; ***, highly significant at $p < 0.001$.

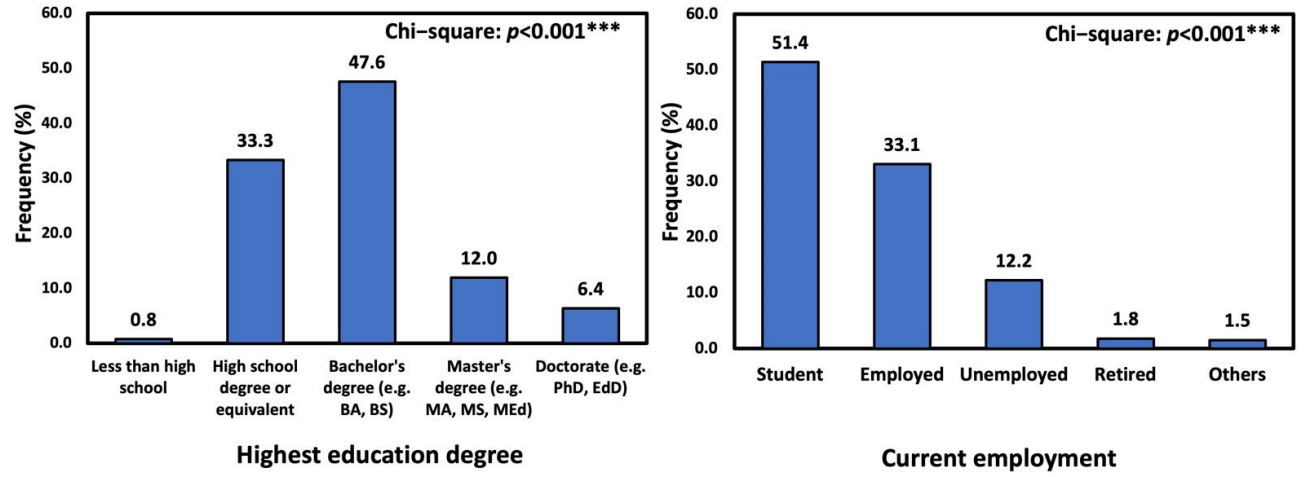


Figure 4. Distribution of responses according to participants' highest educational degree and current employment in frequency; % = frequency percentage from total number of participants; ***, highly significant at $p < 0.001$.

The questionnaire data revealed that the majority of participants were females (85%), with a smaller percentage being males (15%); the difference between their scores was significant, as revealed by the Chi-square test ($p < 0.001$). Regarding the age distribution, most participants (29.8%) fall into the 18–20 years old, followed by the 21–25 years old

(29.0%) and then 35–44 years old (14.2%). The differences between age groups was highly significant, as revealed by the Chi-square test.

The representation decreases steadily in older age groups. Regarding the participants' educational level, the majority of them possess a bachelor's degree (47.6%), followed by those with a high school degree or equivalent (33.3%). A smaller percentage possesses a master's degree (12.0%) or a doctorate (6.4%), with only a minority indicating less than a high school education (0.8%). Regarding the current employment status, most participants were students (51.4%), followed by those employed (33.1%). Unemployment was reported at 12.2%.

3.4. Descriptive Statistics of the Constructs

The respondents were asked to rate their agreement following a five-point Likert scale ranging from one to five concerning knowledge of single-use plastic bags. The descriptive statistics in terms of means, SD, modes, medians, and percentiles (Q1, Q3) are presented in Table 6, in addition to the differences between the five scores on the Likert scale assessed by the Chi-square test.

Table 6. Descriptive statistics of the single-use plastic bag knowledge questionnaire.

Knowledge Question	Mean	SD	Mode	Median	Percentiles		Chi-Square
					25	75	
I plan to regularly purchase products with eco-sustainable packaging.	3.6	1.1	4.0	4.0	3.0	4.0	<0.001 ***
By reducing my consumption of plastics, I can contribute to the preservation of environmental sustainability.	4.0	1.2	4.0	4.0	4.0	5.0	<0.001 ***
Do you think single-use plastic causes harm to the environment?	4.1	1.1	5.0	4.0	4.0	5.0	<0.001 ***
How serious do you think the harm caused by single-use in the natural environment?	3.9	1.0	4.0	4.0	3.0	5.0	<0.001 ***
Do you know that plastic bags can take 10–100 years to degrade in landfills?	3.9	1.2	5.0	4.0	3.0	5.0	<0.001 ***
Plastic packages contain monomers and additive chemicals.	3.6	1.3	4.0	4.0	3.0	5.0	<0.001 ***
I am aware of the impact plastic litter can have on the environment.	4.1	1.0	5.0	4.0	4.0	5.0	<0.001 ***
Knowledge	3.9	0.7	4.0	4.0	3.3	4.4	<0.001 ***
K score	4.1	0.9	5.0	4.0	3.0	5.0	<0.001 ***

***, highly significant at $p < 0.001$; SD = standard deviation; K score = knowledge score.

The findings from Table 6 indicated that participants exhibited considerable knowledge regarding the environmental risks associated with single-use plastics, as demonstrated by their consistently high average scores for different questions. For example, a substantial portion of participants acknowledged that decreasing plastic consumption could have a positive impact on environmental sustainability (mean = 4.0, SD = 1.2) and were aware of the extended period of time it takes for plastic bags to break down in landfills (mean = 3.9, SD = 1.2).

The Chi-square tests yielded statistically significant results ($p < 0.001$) for all items, indicating a strong correlation between respondents' knowledge levels and responses. Table 7 evaluated the frequency distribution of responses to the knowledge questionnaire

on single-use plastics. The data suggested that most participants agreed or strongly agreed with proactive statements regarding reducing plastic consumption and its positive impact on environmental sustainability. For instance, 37.7% of respondents expressed strong agreement, while 43% agreed that reducing their plastic consumption would enable them to make a meaningful contribution to environmental preservation.

Table 7. Frequency and Chi-square values of the single-use plastic bag knowledge questionnaire.

Knowledge Question	Frequency, n (%)					Chi-Square
	1	**2**	**3**	**4**	**5**	
	Strongly Disagree	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**	
I plan to regularly purchase products with eco-sustainable packaging.	27 (6.9)	28 (7.1)	109 (27.7)	142 (36.1)	87 (22.1)	<0.001 ***
By reducing my consumption of plastics, I can contribute to the preservation of environmental sustainability.	34 (8.7)	8 (2.0)	34 (8.7)	169 (43.0)	148 (37.7)	<0.001 ***
Knowledge Question	**No Knowledge**	**Little Knowledge**	**Neutral (Undecided)**	**Medium Knowledge**	**High Knowledge**	**Knowledge Question**
Do you think single-use plastic causes harm to the environment?	12 (3.1)	27 (6.9)	45 (11.5)	121 (30.8)	188 (47.8)	<0.001 ***
Knowledge Question	**Not Severe**	**Mild**	**Moderate**	**Severe**	**Critical**	**Knowledge Question**
How serious do you think the harm caused by single-use in the natural environment?	14 (3.6)	22 (5.6)	88 (22.4)	145 (36.9)	124 (31.6)	<0.001 ***
Knowledge Question	**No Knowledge**	**Little Knowledge**	**Neutral (Undecided)**	**Medium Knowledge**	**High Knowledge**	**Knowledge Question**
Do you know that plastic bags can take 10–100 years to degrade in landfills?	23 (5.9)	41 (10.4)	40 (10.2)	131 (33.3)	158 (40.2)	<0.001 ***
Plastic packages contain monomers and additive chemicals.	30 (7.6)	60 (15.3)	66 (16.8)	126 (32.1)	111 (28.2)	<0.001 ***
Knowledge Question	**No, Not at All**	**I Am a Little Aware**	**I Am Undecided**	**I Am Aware**	**I Am Absolutely Aware**	**Knowledge Question**
I am aware of the impact plastic litter can have on the environment.	4 (1.0)	41 (10.4)	27 (6.9)	156 (39.7)	165 (42.0)	<0.001 ***

***, highly significant at $p < 0.001$; n = number of participants in each category; % = frequency percentage from total number of participants, the numbers between the parentheses in the table represent the percentage of respondents within each category.

The results, which were statistically significant at a p value of less than 0.001 for all questions, demonstrated a notable level of awareness among the respondents regarding the environmental consequences of single-use plastics and a strong inclination towards adopting sustainable practices.

The data from Table 8 indicated a proactive attitude in reducing the consumption of single-use plastics. Most participants indicated a readiness to decrease their utilization of plastic bags (mean = 4.2, SD = 0.8) and to buy environmentally sustainable products (mean = 3.7, SD = 1.1). Once again, the Chi-square tests revealed statistically significant associations ($p < 0.001$), confirming the consistency of these attitudes among the participants.

Table 8. Descriptive statistics of the single-use plastic bag attitude questionnaire.

Attitude Question	Mean	SD	Mode	Median	Percentiles		Chi-Square
					25	75	
Would you like to reduce your own consumption of single-use plastic?	4.1	1.0	5.0	4.0	4.0	5.0	<0.001 ***
How many plastic bags do you buy per week?	3.6	1.1	4.0	4.0	3.0	4.0	<0.001 ***
It's important to avoid single-use plastic bags in our daily life.	4.1	1.0	5.0	4.0	4.0	5.0	<0.001 ***
I am willing to reduce my use of single-use plastic bags	4.2	0.8	4.0	4.0	4.0	5.0	<0.001 ***
I am willing to bring my own reusable bag if there is a reward (e.g., a discount on shopping).	4.2	0.9	5.0	4.0	4.0	5.0	<0.001 ***
I think I am responsible to take care of the environment.	4.2	1.0	5.0	4.0	4.0	5.0	<0.001 ***
Would you prefer to buy a product that doesn't contain microplastics or isn't made with plastic even if it costs more?	3.7	1.1	4.0	4.0	3.0	5.0	<0.001 ***
Attitude	4.0	0.7	4.14a	4.1	3.6	4.6	<0.001 ***
A-score	4.2	0.8	5.0	4.0	4.0	5.0	<0.001 ***

***, highly significant at $p < 0.001$; SD = standard deviation; A-score = attitude score.

Table 9 goes over the attitudes regarding the utilization of disposable plastic bags. A significant proportion of respondents expressed a favorable attitude toward decreasing the usage of plastic bags. Specifically, 43.0% indicated their willingness to decrease their consumption of plastic bags. In comparison, 47.1% expressed their readiness to bring their own reusable bags in exchange for a reward, such as a shopping discount. The participants demonstrated a notable willingness to engage in actions promoting environmental sustainability as long as sufficient incentives exist. The high level of agreement ($p < 0.001$) in response to these questions indicated that the study participants hold positive and consistent attitudes towards environmental responsibility.

Regarding practical behaviors, as indicated in Tables 10 and 11, there was a recognition of the consequences of plastic usage, but the actual behaviors exhibited were diverse. As illustrated in Table 9, the average reaction to using one's own bag while shopping was moderately positive (mean = 3.4, SD = 1.2), indicating the potential for enhancing the adoption of this practice. The frequency distribution (Table 11) corroborated these findings, indicating that many participants occasionally utilized bags provided by stores instead of consistently opting for reusable alternatives.

Table 11 provided a comprehensive understanding of the actual practices of participants in relation to their use of plastic bags. Although there was a general understanding of the environmental consequences, as evidenced by the question "I am aware of the impact plastic litter can have on the environment" in Table 11, the practices exhibited more substantial variations, and the results showed that 42% strongly agreed and 39.7% agreed. For instance, 21.1% of participants utilized their own bags while shopping (27.2% strongly agreed and 23.9% agreed), while 9.2% frequently relied on new plastic bags from the store.

Table 9. Frequency and Chi-square values of the single-use plastic bag attitude questionnaire.

Attitude Question	No Knowledge	Little Knowledge	Neutral (Undecided)	Medium Knowledge	High Knowledge	Attitude Question
Would you like to reduce your own consumption of single-use plastic?	9 (2.3)	22 (5.6)	62 (15.8)	131 (33.3)	169 (43.0)	<0.001 ***
Attitude Question	**Not Severe**	**Mild**	**Moderate**	**Severe**	**Critical**	**0.00**
How many plastic bags do you buy per week?	34 (8.7)	20 (5.1)	76 (19.3)	203 (51.7)	60 (15.3)	<0.001 ***
Attitude Question	**Strongly Disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**	**Chi-Square**
It's important to avoid single-use plastic bags in our daily life.	15 (3.8)	12 (3.1)	70 (17.8)	130 (33.1)	166 (42.2)	<0.001 ***
I am willing to reduce my use of single–use plastic bags.	6 (1.5)	8 (2.0)	45 (11.5)	183 (46.6)	151 (38.4)	<0.001 ***
I am willing to bring my own reusable bag if there is a reward (e.g., a discount on shopping).	10 (2.5)	16 (4.1)	30 (7.6)	152 (38.7)	185 (47.1)	<0.001 ***
I think I am responsible to take care of the environment.	11 (2.8)	21 (5.3)	58 (14.8)	112 (28.5)	191 (48.6)	<0.001 ***
Would you prefer to buy a product that doesn't contain microplastics or isn't made with plastic even if it costs more?	24 (6.1)	30 (7.6)	112 (28.5)	120 (30.5)	107 (27.2)	<0.001 ***

***, highly significant at $p < 0.001$. The numbers between the parentheses in the table represent the frequency percentage of respondents within each category.

Table 10. Descriptive statistics of the single-use plastic bag practice questionnaire.

Practice Question	Mean	SD	Mode	Median	Percentiles		Chi-Square
					25	75	
I usually bring my own bag when I go shopping.	3.4	1.2	4.0	4.0	3.0	4.0	<0.001 ***
Do you use reusable shopping bags?	3.5	1.2	4.0	4.0	3.0	4.0	<0.001 ***
When you are grocery shopping, do you take your own shopping bags or use ones from the store?	3.5	1.2	5.0	4.0	2.0	5.0	<0.001 ***
I think my actions have an impact on the environment.	3.6	1.2	5.0	4.0	2.0	5.0	<0.001 ***
I use a new plastic bag every time I go shopping.	3.1	1.1	3.0	3.0	2.0	4.0	<0.001 ***
Practices	3.4	0.8	3.8	3.4	2.8	4.0	<0.001 ***
P–score	3.4	1.1	4.0	3.0	3.0	4.0	<0.001 ***

***, highly significant at $p < 0.001$; SD = standard deviation; P score = practices score.

Table 11. Frequency and Chi-square values of the single-use plastic bag practice questionnaire.

Practice Question	**No, Not at All**	**I Am a Little Aware**	**I Am Undecided**	**I Am Aware**	**I Am Absolutely Aware**	**Knowledge Question**
I am aware of the impact plastic litter can have on the environment.	4 (1.0)	41(10.4)	27 (6.9)	156 (39.7)	165 (42.0)	<0.001 ***
Practice Question	**Strongly Disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**	**Chi-Square**
I usually bring my own bag when I go shopping.	37 (9.4)	50 (12.7)	103 (26.2)	120 (30.5)	83 (21.1)	<0.001 ***
Do you use reusable shopping bags?	21 (5.3)	63 (16.0)	97 (24.7)	116 (29.5)	96 (24.4)	<0.001 ***
When you are grocery shopping, do you take your own shopping bags or use ones from the store?	11 (2.8)	99 (25.2)	82 (20.9)	94 (23.9)	107 (27.2)	<0.001 ***
I think my actions have an impact on the environment.	16 (4.1)	83 (21.1)	77 (19.6)	103 (26.2)	114 (29.0)	<0.001 ***
I use a new plastic bag every time I go shopping.	33 (8.4)	126(32.1)	128 (32.6)	70 (17.8)	36 (9.2)	<0.001 ***

***, highly significant at $p < 0.001$. The numbers between the parentheses in the table represent the frequency percentage of respondents within each category.

These findings suggested a discrepancy between knowledge and actual behaviours, highlighting a potential opportunity for focused interventions to promote more sustainable actions. The Chi-square values ($p < 0.001$) indicated a significant difference in the responses to practice-related questions. This suggests that although awareness was high, the practical application of the knowledge was inconsistent. Improving practical application is crucial in this context.

3.5. Correlation Tests of Single-Use Plastic Bag KAP

3.5.1. KAP Scores

Figure 5 visually represents the distribution of mean scores and total scores for participants' KAP, with significance levels indicated. The data consistently demonstrated statistical significance ($p < 0.001$), indicating clear differences in participants' responses. Utilizing DMRTs aids in identifying the variability and clustering in the data, indicating a strong methodological approach to comprehending these KAP elements.

The mean total recorded scores for practice and knowledge were the highest, with averages of 28.0 ± 0.25, and 27.2 ± 0.26, which were significantly higher than the mean total attitude scores (17.1 ± 0.21). The same trend was observed in mean scores for practices (4.0 ± 0.68), and knowledge (3.9 ± 0.73) that were significantly higher than mean scores for attitudes (3.4 ± 0.84), as revealed by one way ANOVA and DMRTs at the $p = 0.05$ level.

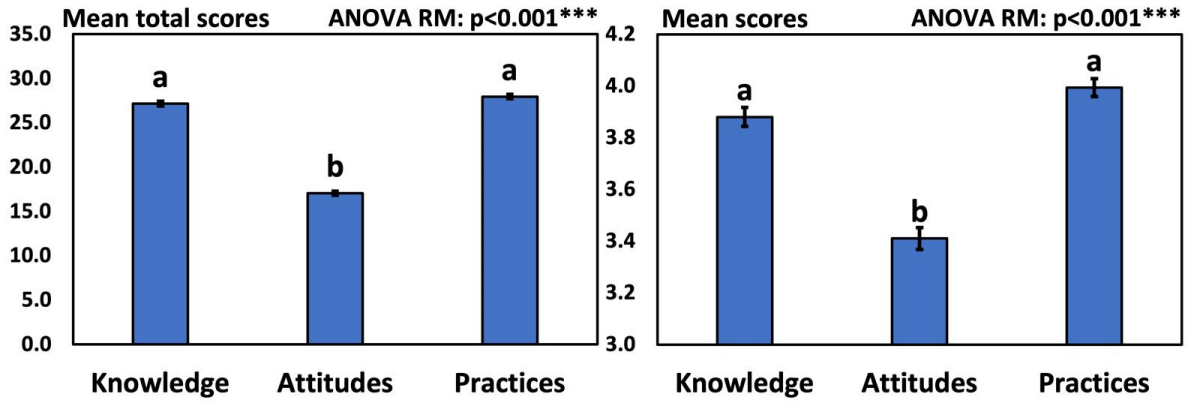


Figure 5. Distribution of responses according to participants' knowledge, attitude, and practice (KAP) in terms of the mean total scores and mean scores analysis of variance (ANOVA), where the p value < 0.001 ***. Bars followed by different letters are significantly different according to Duncan's Multiple Range Test at $p = 0.05$ level.

3.5.2. KAP Scores and Sociodemographic Data

Figure 6A represents the distribution of KAP scores by gender. The results indicated no statistically significant differences in KAP scores based on gender ($p > 0.05$ for KAP * gender interaction). This suggests that gender does not significantly impact the participants' KAP responses. However, in general, the means for KAP for females were higher than for males, and there was a significant relation at $p < 0.001$ *** for KAP.

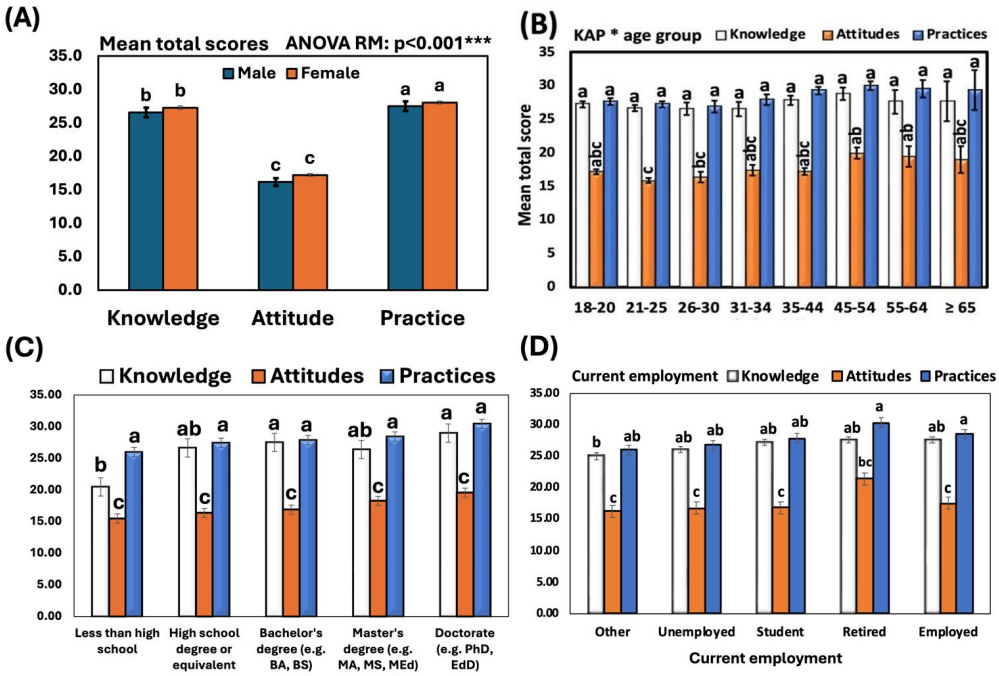


Figure 6. (**A**) Distribution of responses according to participants' knowledge, attitude, and practice (KAP) in terms of the mean total scores between genders. ANOVA RM = Repeated measure analysis of variance. (**B**) The distribution of responses according to participants' KAP in terms of the means of age groups. (**C**) The distribution of responses according to participants' KAP in terms of the means of the education level. (**D**) The distribution of responses according to participants' KAP in terms of the means of current employment. $^{a–c}$ Bars followed by different letters are significantly different according to Duncan's Multiple Range Tests at $p = 0.05$ level. * Highly significant at $p = 0.05$; *** highly significant at $p < 0.001$.

Figure 6B displays a comprehensive visual comparison of KAP scores among different age groups. Statistically significant differences ($p < 0.001$) were observed in the attitude scores, indicating considerable variations in these components among different age groups. The data presented in Figure 4 indicated that individuals in older age groups exhibited higher scores for attitudes and practices regarding the utilization of single-use plastic bags. The mean for age categories (45–54) (M = 27.3 ± 5.1) was the highest among the knowledge, attitudes (M = 19.96 ± 4.1), and practices (M = 30.0 ± 3.2).

Figure 6C visually demonstrates the distribution of KAP scores across different education levels. The graph demonstrated a positive correlation between higher levels of education and improved KAP scores, specifically in attitudes ($p = 0.002$), and practices ($p = 0.047$) related to single-use plastic bags.

Figure 6D concisely depicts the variations in KAP scores across various employment groups. Statistically significant differences ($p = 0.037$) were observed in the attitude scores. The graph illustrates that retired or full-time employees generally exhibited higher KAP scores.

The interrelationships between variables were determined using Pearson's correlation analysis followed by two-tailed significance tests. Accordingly, various sociodemographic parameters showed no correlation with the total mean KAP scores. However, a positive, highly significant correlation existed between mean and total knowledge scores, mean and total attitude and practice scores. Pearson's correlations are also presented as a blue–red heatmap. Red colour indicates a negative correlation, blue colour indicates a positive correlation, white colour indicates no correlation, and grey-boxed colours indicate significant correlations.

The total knowledge score showed a positive, highly significant correlation with practice (r = 0.399; $p < 0.001$), and attitude (r = 0.648; $p < 0.001$) scores. Moreover, the total attitude score was significantly and directly correlated with the practice score (r = 0.487; $p < 0.001$). These results supported a positive significant correlation between the three main parameters, KAP, as revealed by Pearson's correlation coefficients and the two-tailed significance test (Table 12).

Table 12. Mean total scores for single-use plastic bag knowledge, attitudes, and practices according to the total knowledge, attitude, and practice means, p value < 0.005.

	Age	**Gender**	**Education**	**Employ.**	**Total–K**	**Total–P**	**Total–A**	**Mean–K**	**Mean–P**	**Mean–A**
Age		<0.001 ***	<0.001 ***	<0.001 ***	0.199	0.001 ***	0.002 **	0.204	0.001 ***	0.002 **
Gender	−0.255		<0.001 ***	<0.001 ***	0.338	0.078	0.427	0.321	0.078	0.439
Education	0.588	−0.216		<0.001 ***	0.089	<0.001 ***	<0.001 ***	0.093	<0.001 ***	0.008 **
Employ	0.499	−0.316	0.423		0.093	0.094	0.021	0.093	0.094	0.024 *
Total–K	0.066	0.049	0.087	0.086		<0.001 ***	<0.001 ***	<0.001 ***	<0.001 ***	<0.001 ***
Total–P	0.168	0.090	0.198	0.086	0.399		<0.001 ***	<0.001 ***	<0.001 ***	<0.001 ***
Total–A	0.161	0.041	0.137	0.118	0.648	0.487		<0.001 ***	<0.001 ***	<0.001 ***
Mean–K	0.065	0.051	0.086	0.086	0.999	0.400	0.650		<0.001 ***	<0.001 ***
Mean–P	0.168	0.090	0.198	0.086	0.399	1.000	0.487	0.400		<0.001 ***
Mean–A	0.161	0.040	0.136	0.115	0.648	0.483	0.999	0.650	0.483	

Total–K = knowledge total marks, which is the total of the knowledge questions' marks, total–P = practice total marks, which is the total of the practice questions' marks, total–A = attitude total marks, which is the total of the attitude questions' marks, mean–K = mean of the total knowledge marks, mean–P = mean of the total practices marks, mean–A = mean of the total attitudes points. *, **, *** significant at $p < 0.05$, <0.01, <0.001.

Figure 7 displays a heatmap illustrating the correlation coefficients between different study variables, such as demographic factors and KAP scores. The red colour represents negative correlations, while blue colour represents positive correlations. Additionally, significant correlations were highlighted using grey boxes. This visual aid facilitates the rapid identification of significant influences and relationships, such as the favourable effect of education on all three KAP scores and the intricate interaction between age, knowledge, and practice.

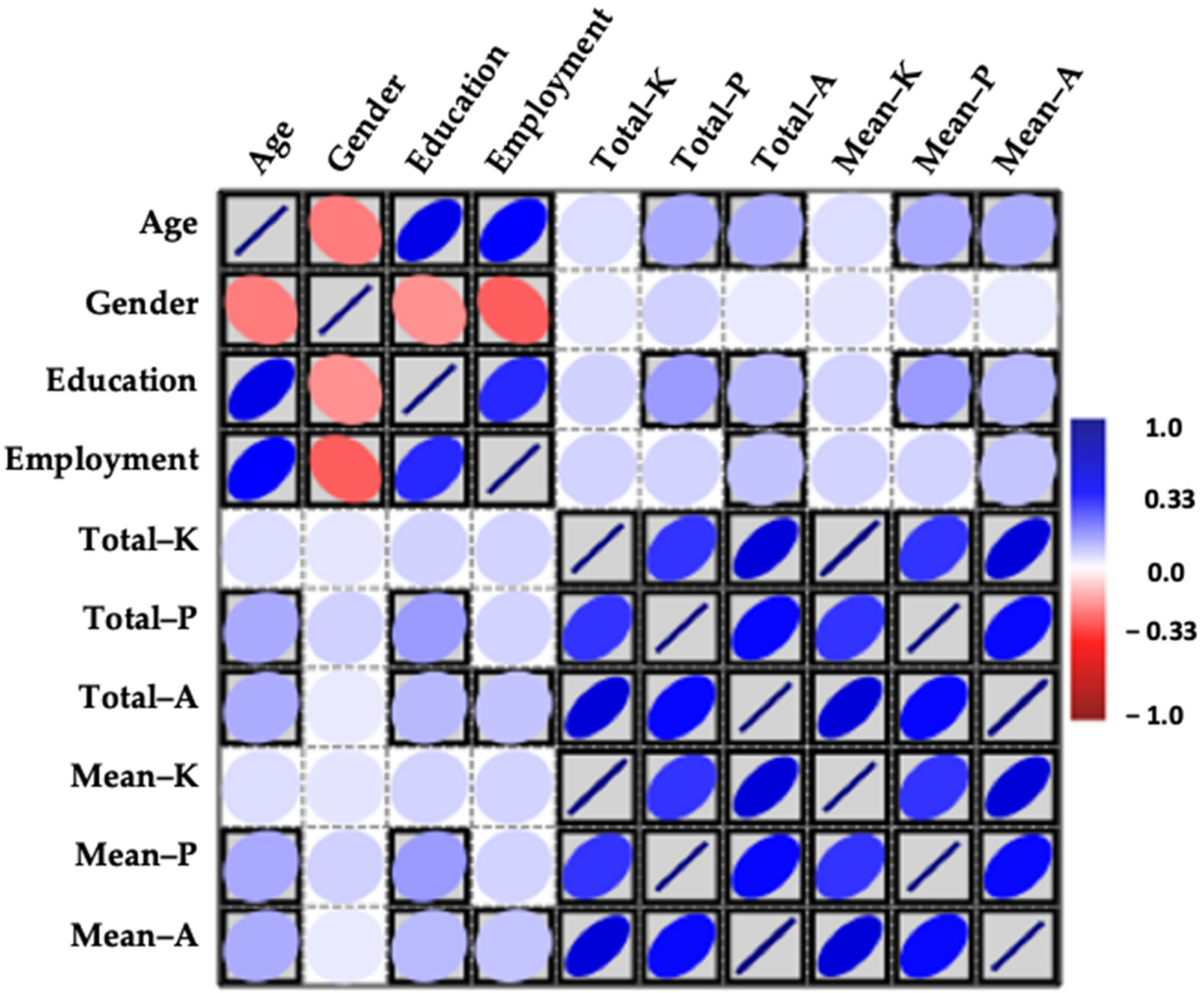


Figure 7. Heatmap presenting the interrelationships between study variables including age, gen-der, education employment status, total knowledge scores (total−K), total attitudes scores (total−A), total practices scores (total−P), mean knowledge scores (mean−K), mean practice scores (mean−P), and mean attitudes scores (mean−A). Red colour indicates a negative correlation, blue colour indicates a positive correlation, and white colour indicates no correlation. Grey boxed colours indicate significant correlations as revealed by two−tailed test.

Figure 8 expands upon the correlation analysis conducted in Figure 8 by examining additional variables or a more specific subset of the study population. The heatmap employs colour coding to represent the intensity and direction of relationships, serving as a valuable tool for identifying crucial factors that influence environmental behaviours. The relationship between higher levels of education and improved environmental practices is particularly significant, indicating that focused educational interventions could yield highly impactful results.

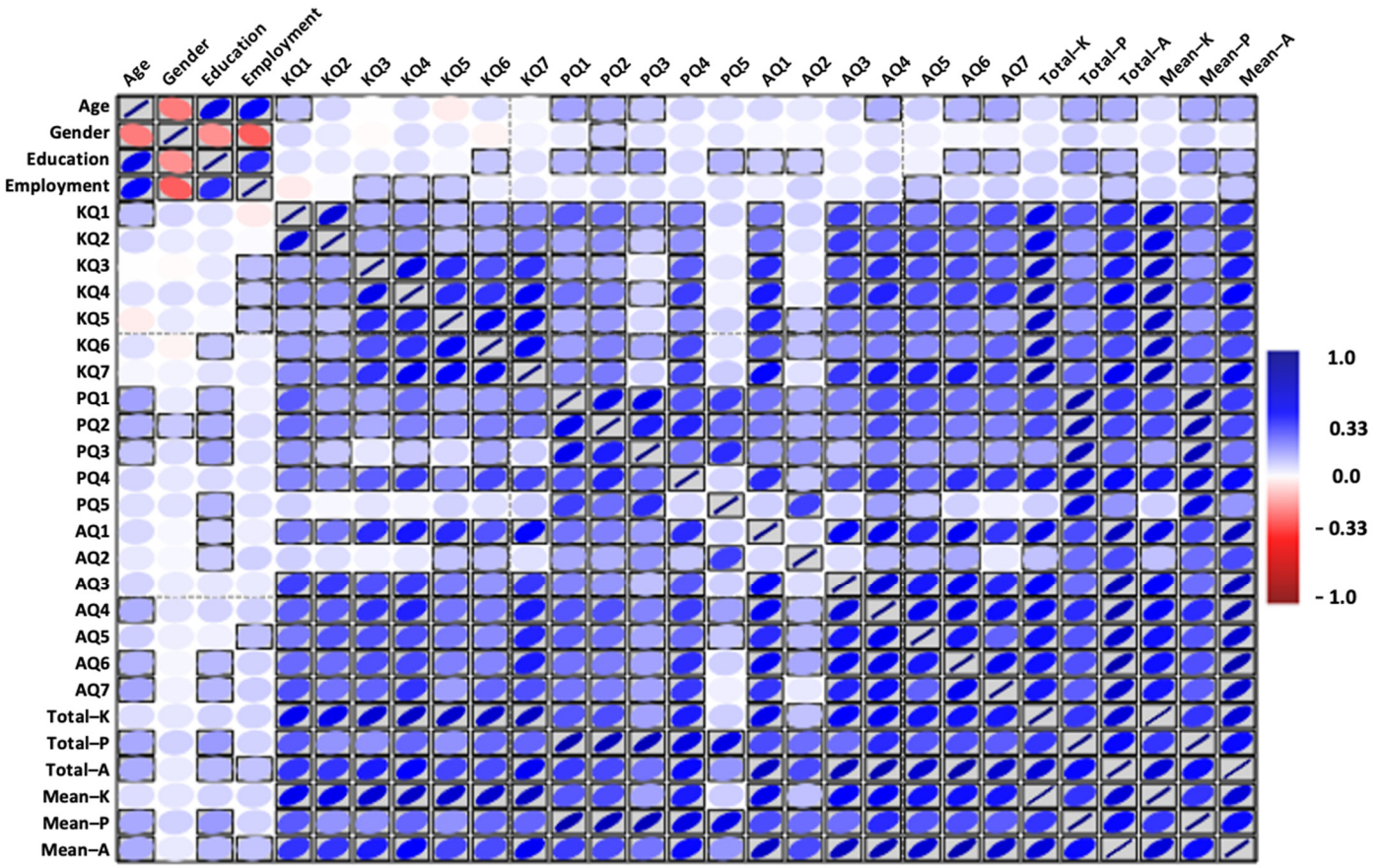


Figure 8. Heatmap presenting the interrelationships between study variables, where red indicates a negative correlation, blue indicates a positive correlation, and white indicates no correlation. Grey boxed colours indicate significant correlations as revealed by two-tailed significance test, KQ1–KQ7 = knowledge questions, PQ1–PQ5 = practices questions, AQ1–AQ7 = attitudes questions, total–K = total knowledge scores, total–A = total Attitudes scores, total–P = total practices scores, mean–K = mean knowledge scores, mean–P = mean practice scores and mean–A = mean attitudes scores.

3.6. PLS-SEM

The current study relied on using SEM with a two-step approach. The first step involved the measurement model, which assesses the loading of indicators on the latent variables within a single model and determines its fit. The goodness-of-fit indicators are presented in Table 13.

Table 13. The goodness-of-fit indicators for structural equation modelling (SEM).

Chi-Square (*p* Value)	df	RMSEA	SRMR	CFI	TLI	NNFI
870 (<0.0001 ***)	149	0.012	0.094	0.954	0.947	0.947

*** highly significant at $p < 0.001$, df = degree of freedom, RMSEA = root mean square error of approximation, SRMR = standardized root square residual, CFI = comparative fit index, TLI = Tucker–Lewis index, NNFI = non-normed fit index.

The results indicated an acceptable fit based on the Tucker–Lewis index (TLI) and non-normed fit index (NNFI), while the fit was in the ideal range for the comparative fit index (CFI index), as its value exceeded 0.95. The root mean square error of approximation (RMSEA) value was good, and the standardized root square residual (SRMR) index was close to zero, indicating a good fit.

However, the Chi-square value was significant, suggesting poor fit according to this index, likely due to its sensitivity to sample sizes exceeding 200 cases. The standardized loadings of the indicators on the latent factors are presented in Table 14.

Table 14. The standardized loadings of the indicators on the latent factors.

Latent Variable	Indicators	Loadings	SE	Z	*p* Value
Knowledge	KQ1	1.0	0.000	--	--
	KQ2	1.094	0.068	16.04	<0.001 ***
	KQ3	1.103	0.082	13.46	<0.001 ***
	KQ4	1.206	0.083	14.59	<0.001 ***
	KQ5	1.022	0.084	12.18	<0.001 ***
	KQ6	1.007	0.076	13.25	<0.001 ***
	KQ7	1.295	0.080	16.21	<0.001 ***
Practices	PQ1	1.000	0.000	--	--
	PQ2	0.924	0.062	14.88	<0.001 ***
	PQ3	0.782	0.055	14.16	<0.001 ***
	PQ4	0.993	0.065	15.21	<0.001 ***
	PQ5	0.544	0.064	8.54	<0.001 ***
Attitudes	AQ1	1.000	0.000	--	--
	AQ2	0.362	0.070	5.17	<0.001 ***
	AQ3	0.996	0.038	26.37	<0.001 ***
	AQ4	0.1089	0.041	26.91	<0.001 ***
	AQ5	0.888	0.048	18.60	<0.001 ***
	AQ6	1.000	0.041	24.64	<0.001 ***
	AQ7	0.853	0.044	19.45	<0.001 ***

***, highly significant at p < 0.001, SE = standard error, Z = Z–statistic value, KQ1–KQ7 = knowledge questions, PQ1–PQ5 = practices questions, AQ1–AQ7 = attitudes questions.

All loadings for the measurement model were statistically significant, indicating that none of the indicators should be excluded from the analysis. All indicators under the latent variables included in the analysis should be retained. The next step in the SEM is to test the structural model. The goodness-of-fit indicators for the structural model are presented in Table 15.

Table 15. The goodness-of-fit indicators for the structural model.

Chi-Square (*p*-Value)	df	RMSEA	SRMR	CFI	TLI	NNFI
2446 (<0.001 ***)	1375	0.062	0.004	0.993	0.977	0.977

***, highly significant at $p < 0.001$, df = degree of freedom, RMSEA = root mean square error of approximation, SRMR = standardized root square residual, CFI = comparative fit index, TLI = Tucker–Lewis index, NNFI = non-normed fit index.

The goodness-of-fit indicators for the structural model were all within the ideal range for all indices. However, the Chi-square index was affected by sample size, the nature of data normality, or outliers, which resulted in a statistically significant value, indicating a poor fit. The values of the direct effects between the independent and dependent variables are presented in Table 16.

Table 16. The values of the direct effects between the independent and dependent variables.

Dependent	Predictors	Effect Size	SE	Z	*p* Value
Practices	Attitudes	0.519	0.089	5.82	<0.001 ***
Practices	Knowledge	0.152	0.108	4.41	0.049 *
Attitudes	Knowledge	0.997	0.067	14.88	<0.001 ***

* highly significant at the 0.05 level. *** highly significant at $p < 0.001$. SE, standard error, Z, Z-statistic value.

There was a direct causal effect from the variable "attitudes" to "practices", with a value of 0.519, which was a positive and statistically significant effect. There was a direct causal effect from the variable "knowledge" to "practices", with a value of 0.152, which was a positive and statistically significant effect. There was a direct causal effect from the variable "attitudes" to "knowledge," with a value of 0.997, which was a positive and statistically significant effect.

The graphical representation illustrates the direct causal effects between the independent and dependent variables. Figure 9 illustrates the initial conceptual model of the relationship between KAP towards single-use plastic bags. The constructs (K = knowledge, A = attitudes, P = practices) are represented as boxes, and the hypothesized relationships are depicted as directed arrows with path coefficients. Each construct was linked to its respective indicators, listed within the boxes. The R^2 values indicated the proportion of variance explained in the attitudes and practices constructs by their predictors.

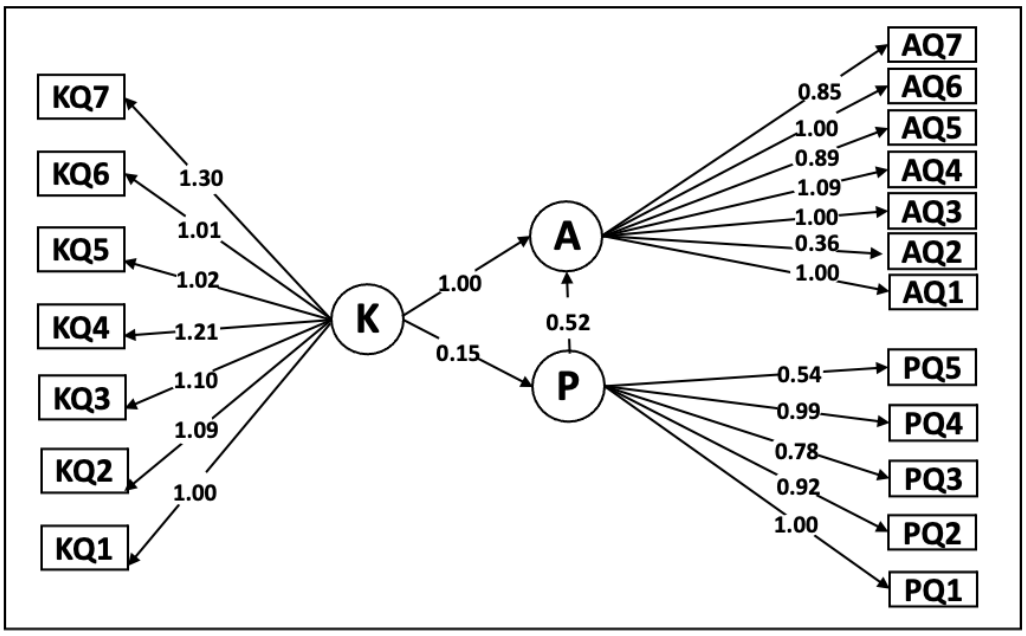


Figure 9. The structural equation model with its significant pathways. K = knowledge, A = attitudes, P = practices, KQ1–KQ7 = knowledge questions, AQ1–AQ7 = attitude questions, PQ1–PQ5 = practice questions.

The knowledge construct was best measured by items K7 and K4. When compared to other items, items P1 and P4 had the greatest loadings (1.00 and 0.99, respectively) for the practice construct, while indications A4 (1.09), and all A1, A3 and A6 (1.00) have the highest loadings for the attitude construct (Figure 9).

By leveraging PLS-SEM, we were able to uncover significant insights into the factors influencing sustainable behaviours related to single-use plastic bags in the UAE, providing a robust foundation for developing targeted interventions and policies. According to previous results, the main conclusions may be drawn from the results, and they are as follows: The findings indicated that, in terms of KAP toward single-use plastic bags, there was a positive awareness of KAP toward single-use plastic bags. As a result, when implementing KAP related to single-use plastic bags, people are aware of the impact of plastic on the environment and try to reduce waste by bringing their own bags when they go shopping; in addition to minimizing plastic waste, they tend to use reusable shopping bags.

There was a positive overview of the awareness and attitudes towards reducing the use of single-use plastic bags. However, they also emphasized the difficulties in effectively translating this awareness into consistent and practical actions. The highlighted results were a positive significant correlation between the knowledge mean, and scores and attitude and practice mean and scores. In addition, the total knowledge score showed a highly

significant correlation with practices and attitudes. Moreover, the total attitude score was directly correlated with practices, and regarding sociodemographics, there was a correlation between higher levels of education and improved KAP scores, specifically in attitudes and practices. However, the practice score was higher than the attitude score.

4. Discussion

The current KAP research on single-use plastic bags significantly improves our understanding of this pressing environmental issue. The findings presented a valuable understanding of the correlation between individuals' KAP concerning single-use plastic bags in the UAE.

Unlike previous studies that explored the connections between KAPs regarding single-use plastic bags, we utilized a second-generation statistical method called PLS-SEM to investigate the proposed relationships. PLS-SEM is an appropriate choice for research design and predicting causal links in situations where the sample size is small and the topic field is new. It is the most frequently employed SEM approach for such circumstances. Typically, a PLS-SEM is evaluated and understood through a two-stage process. The initial step involves assessing and improving the adequacy of the measurement model, followed by evaluating and reviewing the structural model. Ensuring the metrics' reliability and validity is essential prior to making any inferences from the structural model. We evaluated the validity of the following research questions:

RQ1: What are the KAP levels of single-use plastic bags in the UAE? Are there any correlations among KAP concerning single-use plastic bags in the UAE?

RQ2: Are there relationships between sociodemographic characteristics and KAP regarding the usage of single-use plastic bags in the UAE?

Knowledge of single-use plastic bags use in the UAE has a moderating influence on the connection between attitudes and practices. Specifically, a positive attitude towards single-use plastic bags has a beneficial impact on practices related to their use. The proposed model for KAP regarding single-use plastic bags demonstrated a strong fit and was deemed satisfactory. The diagram illustrates the interconnection between the variables of food safety KAP in a structural model. The PLS-SEM method was utilized for conducting hypothesis testing.

The present study underscores the influence of sociocultural factors on attitudes and behaviours related to disposable plastic bags. For example, the sociocultural context examined in a previous study in UAE found that Sharjah's environmental practices are affected by its culture [40]. On the other hand, in our current study, participants were ensured to represent the entire country and varied in age from 18 years to older to ensure generalization. Economic factors could affect environmental perception, such as in a study in Greece and Lebanon, which discussed the economic factors regarding single-use plastic bags with the possibility of alternative sustainable and biodegradable materials [42].

In our study, there was no relation with the economic factors reflected in employment status. A study by Hamza and Mahmoud [60] in Assiut City, Egypt, revealed that individuals with higher levels of education exhibited higher knowledge scores. This underscores the pressing need for enhanced education about environmental hazards [60]. Likewise, our study has shown a positive correlation between higher levels of education and improved KAP scores, specifically in attitudes ($p = 0.002$), and practices ($p = 0.047$) related to single-use plastic bags.

A different KAP study by Ismail et al. [38] regarding plastic usage during COVID-19 showed that the knowledge level was associated with age groups and the educational level, while attitudes were related to the educational level [38]. Although there was no relationship between sociodemographic data and the KAP in the current study, another study conducted in Vietnam by Giao and Thien [61] on the management of household solid waste revealed that plastic bags made up a significant portion of the waste, with 42.7% of the sample, and there were relationships between the educational level and age and KAP results [61]. Moreover, another study by Kittu et al. [62] was conducted to assess the KAP

levels of Indian residents regarding the utilization and regulations of single-use plastics. The study revealed a notable increase in the perception of the law prohibiting the use of plastic bags among younger individuals, females, and those with higher levels of education and occupational status ($p = 0.01$), almost similar to the present study's results [62].

A study conducted in Malaysia by Abdullah et al. [12] found a high level of awareness (97.6%) about the excessive use of plastic bags; their results showed that there was no relationship between knowledge and practices, while in the current study, there was a positive correlation between knowledge and practices. However, other research findings suggested a clear correlation between knowledge and practices [60]. Another study by Tharu and Shrestha [7] in Kathmandu Valley, Nepal, regarding the usage of plastic products among undergraduate students, suggested that they have inadequate knowledge and attitudes toward good practices [7]. On the other hand, in the present study, the average scores suggested a favourable inclination towards sustainability with very good KAP, all surpassing the midpoint. In a study in Northeast Malaysia, the knowledge score regarding street food hawkers supported the single-use plastic products was 9.2 ± 17.8 with the SD [63]. On the other hand, in the present study, the knowledge score was 3.89 ± 0.7 with the SD.

In contrast, a previous study conducted by Ismail et al. [38] in Malaysia before the COVID-19 pandemic on disposable plastic bags identified a lack of commitment to sustainable knowledge, highlighting the need for more individuals to adopt sustainable behaviours to reduce the usage of disposable plastic bags. While attitudes were linked to the educational level, the knowledge level was found to be related to age groups and the level of education [38]. Ismail et al. [38] study found a significant relationship between attitudes and practices, as well as knowledge and attitudes (p value < 0.05) [38]. Similarly, in the current study, the results showed a positive significant relationship between knowledge and attitudes. In contrast, another study by Coco Chin et al. [37] in Malaysia indicated a prevalent result where respondents exhibited low knowledge and practices for plastic pollution [37]. Moreover, another study by Kombiok and Naa Jaaga [64] in Ghana regarding the disposal of plastic waste showed that 87% of respondents have a negative attitude [64]. In addition, according to a Saudi Arabian study on tourists' behavioural intentions to reduce plastic waste, attitudes did not greatly affect the prediction of environmental behavioural intentions [65].

Several studies have examined the effects of some strategies in countries that aim to reduce plastic pollution. For example, in Thailand, 75 prominent retail establishments have launched a campaign to cease the distribution of complimentary disposable plastic bags [66]. Panyagometh et al. [66] assessed the current situation and effectiveness of the plastic bag ban campaign in Bangkok and Phuket in Thailand, and they estimated the quantity of plastic bags used in these areas. Additionally, their study aimed to understand consumer behaviours regarding plastic bag consumption and management by utilizing a KAP model. The finding was that attitudes were more crucial than knowledge towards pro-environmental behaviours [66].

On the other hand, a survey in Cambodia was conducted to assess the added charges for plastic bags by supermarkets. The study demonstrated that inadequate KAP poses obstacles to the objective of decreasing plastic consumption in supermarkets [67]. These strategies were aimed at correlating knowledge with practices. Contrarily, in the present study, the total knowledge score showed positive, highly significant correlations with practice ($r = 0.399$; $p < 0.001$), and attitude ($r = 0.648$; $p < 0.001$) scores. A study conducted in Sharjah, UAE, focused on the KAP of sustainability among university students [40]. The findings revealed a favorable outlook about the significance of promoting sustainable practices [40]. A KAP study in the Maldives regarding single-use plastic usage demonstrated that 20.9% agreed to use reusable bags instead of plastic shopping bags [68]. Similarly, in the current study, 29.5% agreed to use reusable shopping bags.

The results of our research could be advantageous for numerous educators and public applications. These measures encompass limiting the production and usage of plastic and

promoting the adoption of biodegradable alternatives to plastic bags to discourage their utilization. The education intervention may incorporate extensive plastic use awareness programs that prioritize the ecological consequences of plastic wastes and promote sustainable practices. Surprisingly, we have found unexpected results; although there was a strong level of knowledge (with an average rating of 3.9 out of 5) regarding the environmental impact of single-use plastics, people do not always take action accordingly (with an average practice score of 3.4). This implies that simply being aware of something may not be enough to cause a change in behaviour.

The significance of our findings is paramount for both educators and the general public. Educators should incorporate comprehensive programs that tackle plastic consumption into their curricula. This could entail implementing school-wide initiatives and incorporating environmental awareness into various academic disciplines. Prioritizing the emphasis on the enduring ecological ramifications of plastic usage and offering practical methods to diminish one's plastic footprint is crucial. Sustainable practices are driven by public engagement and awareness campaigns, as well as collaboration between local governments, non-government organizations, and communities. They can coordinate efforts to clean up and recycle materials to decrease the use of disposable plastics. Additionally, they employ social media and public service announcements to raise awareness and encourage widespread participation in creating a sustainable future. One of the significant limitations is the lack of research on single-use plastic bags in the UAE. The current literature on single-use plastic bags is predominantly centralized in regions outside the UAE, and this is a limitation of the current research in comparing our study with a previous study to indicate if there have been any improvements over the years.

Our findings suggested several research areas to build on our work. First, longitudinal studies would help assess the KAP over time. These studies can assess the long-term efficacy of single-use plastic reduction education and policy. However, there are many important interventions that the UAE has already established [40], for example, introducing sustainability courses in the university to increase awareness [69] and a strategy for integrated plastic waste management in the UAE [41]. We also recommend that experimental designs be evaluated by educational campaigns, financial incentives, and policy changes to reduce single-use plastic misuse. For instance, testing the effects of higher plastic bag taxes or reusable alternatives could reveal the best strategies [70–72].

Deeper insights into single-use plastic bags require qualitative studies. As shown in our findings, these studies can explain why awareness does not always lead to action. Focus groups and interviews with different demographic groups can reveal behaviour change barriers and reveal public attitudes and practices. Comparisons between countries or regions can also reveal cultural and policy differences that affect plastic use and waste management. These could help create culturally and contextually appropriate interventions [70–72].

5. Conclusions

In conclusion, from all results, there is a positive overview of the awareness and attitudes towards reducing the use of single-use plastic bags. However, our results emphasized the difficulties in effectively translating this awareness into consistent and practical actions. The highlighted result is a positive significant correlation between the knowledge mean, scores and attitude, and practice mean and scores. In addition, the total knowledge score showed a highly significant correlation with practices and attitudes. Moreover, the total attitude score is directly correlated with practice.

Regarding sociodemographic, there is a correlation between higher levels of education and improved KAP scores, specifically in attitudes and practices. However, the practice score is higher than the attitude score. The notable statistical results from all the tables emphasized the need for ongoing educational and policy-driven initiatives to close the disparity between attitudes and practices regarding single-use plastic bags. The limitation of the current study is the scarcity of comprehensive research on this subject. The study addresses a notable research need by specifically examining the UAE and provides accurate

findings that may inform regional interventions and policy strategies. Furthermore, this study extensively examines the connections between KAP and single-use plastic bags, as opposed to previous studies that may have focused on specific aspects such as knowledge or attitudes. Therefore, it provides a thorough depiction of the interplay between these elements within the framework of the UAE.

Our research will benefit policymakers in establishing suitable interventions. The most effective way to increase KAP is to introduce a sustainability course, which has already been established in the university [69]. In addition, the strategy for integrated plastic waste management in the UAE is to achieve zero emissions [41]. Hence, we recommend following up on these strategies and sustainability course education. Moreover, we can check before and after implementing these strategies. For future studies, longitudinal studies, experimental designs, and qualitative methods are needed. These suggestions seek to address the consumption of single-use plastics to expand our research and contribute to a sustainable future. Overall, the current findings highlight a significant degree of consciousness and a favourable disposition toward minimizing the use of plastic among the participants. Nevertheless, there is a noticeable disparity between the knowledge and attitudes held by individuals and their actual behaviours, underscoring the necessity for additional interventions to promote more sustainable practices regarding single-use plastics. The notable Chi-square values observed in all our tables support the dependability of these findings and indicate that these patterns indicate the larger population surveyed in our study. The current research will benefit not only one aspect of the environment but also marine environments, desert environments, and sustainability by reducing plastic pollution. Due to its significance, the KAP model for single-use plastic bags is widely applied. However, from the perspective of the UAE, the KAP model is lacking when it comes to single-use plastic bags.

Reducing single-use plastic bags has many long-term sustainability benefits. It helps reduce plastic pollution, a major environmental issue affecting terrestrial and marine ecosystems. Additionally, by reducing the carbon footprint of extracting and processing these resources, this conservation effort helps mitigate climate change. Reusable alternatives and recycling are part of a circular economy, which reduces waste and promotes sustainability.

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An Assessment of the Knowledge, Attitudes, and Practices Toward General Waste Segregation among the Population of the United Arab Emirates

Shahad K. Hassooni [1], Khaled A. El-Tarabily [1], Abdelghafar M. Abu-Elsaoud [2,3] and Seham M. Al Raish [1,*]

[1] Department of Biology, College of Science, United Arab Emirates University, Al Ain 15551, United Arab Emirates; 202002407@uaeu.ac.ae (S.K.H.); ktarabily@uaeu.ac.ae (K.A.E.-T.)
[2] Department of Biology, College of Science, Imam Mohammad Ibn Saud Islamic University (IMSIU), Riyadh 11623, Saudi Arabia; amsmohamed@imamu.edu.sa
[3] Department of Botany and Microbiology, Faculty of Science, Suez Canal University, Ismailia 41522, Egypt
* Correspondence: seham.alraish@uaeu.ac.ae

Abstract: Increases in the human population and economic development have led to a rise in waste production, which poses significant environmental risks and presents a pressing global issue in waste management. Among other countries, this situation affects the United Arab Emirates (UAE). On the other hand, poor waste segregation practices can result in failed waste recycling efforts, leading to the excessive use of resources and worsening issues (such as energy consumption, global warming, and sustainable development). Waste segregation is a crucial step in waste management, which involves dividing waste according to its characteristics and type. By following this procedure, recycling effectiveness is increased, the environmental impact is decreased, and hazardous material disposal is ensured. Beneficial waste segregation reduces contamination, making it possible to recover valuable materials and thus use fewer landfills. Even though the failings in waste segregation are a severe issue, insufficient research has been carried out. This includes research on the knowledge, attitudes, and practices (KAP) of people living in the UAE regarding waste segregation, information which is crucial to developing a successful intervention to address this problem. The current study evaluated the KAP concerning waste segregation among UAE citizens and identified correlations between KAP variables, with the primary aim of filling a research gap, while analyzing the correlations between sociodemographic characteristics and KAP levels, which was the secondary aim. This was accomplished by a cross-sectional study conducted all over the UAE. Data were collected from 391 participants using a five-point Likert scale questionnaire that was developed from previous research and investigated sociodemographic characteristics, waste segregation practices (5), attitudes (5), and knowledge (5). UAE University's ethical committees approved this study (ERSC_2024_4360) for research, and the results were confirmed through statistical analyses and Cronbach's alpha testing. The inclusion criteria targeted residents of the UAE who were 18 years of age or above, and the survey was distributed via an online platform (Google Forms) with non-probability sampling. G*Power statistical power analysis estimated a minimum sample size of 385 participants. To identify correlations in the results, a structural equation model (SEM) and SPSS, such as Chi-square tests and Spearman correlation coefficients, were used to assess the associations between KAP variables. These tests were chosen for their robustness in handling categorical and continuous data, respectively. A notable majority (84.1%) of the participants were female, and 15.9% were male; the gender difference was highly significant, as revealed by the Chi-square test. Most participants (67.0%) fell into the 18–24 age group. The highest level of education reported was a bachelor's degree (47.3%). The parents' educational levels showed a relatively high level of education, with more than half having at least a high school degree or higher: father's education level (67.2%) and mother's education level (73.1%). Most participants were students (58.8%), but a significant portion of the sample was employed (25.1%). Unemployment was reported at 12.3%. The parents' employment statuses showed a higher percentage of unemployed mothers (49.4%) compared to fathers (6.9%). The average scores suggested a favorable inclination toward sustainability ((mean ± standard deviation (SD) for knowledge, 3.59 ± 0.78; poor knowledge, 3.6%; and excellent knowledge, 16.9%), attitudes

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(3.73 ± 0.77; poor attitudes, 2.8%; and excellent attitudes, 22.5%), and practices (3.62 ± 0.76; poor practices, 2.3%; and excellent practices, 16.4%), with all the means surpassing the midpoint. In the correlation test, the current study demonstrated positive correlations between knowledge and attitudes (r = 0.666, $p < 0.001$) and between knowledge and practices (r = 0.682, $p < 0.001$). Also, a positive correlation (r = 0.159, $p < 0.001$) was found between general waste segregation KAP and sociodemographic variables, with a significant correlation (r = 0.110) between attitudes and gender. These findings emphasize the possibility of using focused educational and policy interventions to improve waste segregation behaviors. An additional investigation is advised to delve into the fundamental mechanisms behind these correlations and devise customized approaches to encourage sustainable waste management practices among various demographic groups in the UAE.

Keywords: attitude; knowledge; practice; recycling; solid wastes; sustainability; waste management; waste segregation

1. Introduction

The increase in the human population and economic development have led to a rise in waste production, with 2 billion tons of total waste produced in 2016 [1], which has risen to 7–9 billion tons of waste produced today [1,2]. This poses significant environmental risks and presents a pressing global issue in waste management [3,4]. On the other hand, poor waste segregation practices can result in failed waste recycling efforts [5,6]. These may arise due to a deficiency of modernized methods, techniques, and systems or a slow change from outdated waste management models [6]. Furthermore, inadequate infrastructure, limited public awareness, insufficiently feasible projects, and public policies that fail to achieve the intended purpose have been identified as contributing factors [7].

Poor waste management methods were attributed to insufficient training for staff, resource shortening, and inadequate budget support [8], leading to the excessive use of resources and worsening issues such as energy consumption, global warming, and sustainable development [9]. Therefore, effective interventions are necessary to address these challenges [10]. In 2016, the United Nations adopted 17 Sustainable Development Goals (SDGs) [11], with 8 directly or indirectly related to waste management [12]. This highlights the importance of addressing waste challenges comprehensively [13]. The first step in comprehensive waste management is understanding the general waste segregation procedure and what affects this procedure [14].

General waste segregation is a method that promotes circular economy principles and ecological conservation as economies expand [15]. The process involves separating reusable and recyclable materials from the general waste [16]. These practices involve classifying waste into distinct groups: paper, plastic, glass, metal, etc. [17]. Additionally, municipal solid waste (MSW) can be categorized into seven primary groups: organics, paper/boards, plastics, glass, metals, textiles, and inert materials [17]. Then, organic waste is sorted into several categories, such as garden trash, animal by-products, and dairy waste, to be transformed into bioenergy and organic fertilizer [16,18,19]. Doing so can conserve landfill space, minimize environmental and public health impacts, and make resources more easily accessible through the recycling field [6,16]. However, it is a complex procedure requiring careful attention to detail and specific techniques to ensure optimal effectiveness and achieve the desired outcomes [10,15].

In addition, knowledge, attitudes, and practices (KAP), concerning waste segregation can impact the effectiveness of waste segregation, as has been studied in several countries, such as China, where researchers found that knowledge of waste segregation significantly influences household waste sorting practices [10]. According to the study's results, practices and knowledge have a significant positive relationship ($p < 0.01$). Additionally, a high level of knowledge and positive attitudes regarding waste sorting will improve practices in the field [10].

On the other hand, at Hamadan University in Iran [4], a positive correlation was observed between attitude and knowledge, as well as practices. Their study highlights the interplay between KAP, suggesting that a positive attitude toward waste management is associated with more excellent knowledge and better waste sorting practices. Additionally, knowledge levels influence waste sorting performance [4].

Similarly, Malaysia emphasizes the significant impact of attitude on waste separation behavior among households [20]. Kasmuri et al. [20] suggest that a favorable attitude significantly affects waste separation behavior. This underscores the importance of promoting positive attitudes toward waste management [20]. In South Africa, gender was identified as a significant factor influencing waste separation practices [21]. Roos et al. [21] reported a statistically significant relationship between gender and waste separation behavior ($p = 0.02$) [21].

The study of KAP research on waste segregation in the United Arab Emirates (UAE) sheds light on a serious part of the environment and sustainable economic development [22,23]. Waste management is a pressing global issue in the UAE [23]. Understanding the KAP of the population toward waste segregation is essential for designing effective policies and initiatives to address this issue and try to minimize it [24,25], which will close the economic wasting loop that results from wasting resources [26,27]. On the other hand, SDG can be achieved by implementing the KAP results on the development plan for achieving the SDG [28–31].

Moreover, in the UAE, one study examined the impact of age on residents' knowledge of waste management practices. Contrary to expectations, they found no significant difference in knowledge levels across age groups ($p > 0.05$). This suggests that age may not be a substantial determinant of waste management knowledge in the UAE, emphasizing the need for broader educational initiatives targeting diverse demographic groups [32].

In addition, Dubai in the UAE mostly employs small scale recycling initiatives to handle materials such as steel, plastic, and wood [33]. Furthermore, the city utilizes specialized landfills to manage construction and demolition (C & D) trash effectively. Dubai Municipality (DM) implements regulations for sustainable construction to reduce CO_2 emissions and energy consumption. These regulations mandate using environmentally friendly materials and thermal insulation [33]. To mitigate the adverse environmental impacts of cement factories, DM has also enforced the utilization of eco-friendly cementitious materials [33].

On the other hand, in Ajman, UAE, the emirate's rapid population growth and industrial expansion have led to a significant increase in garbage output, posing a critical problem for waste management. The planning department and the Ajman municipality have initiated several projects to improve waste management protocols to effectively tackle these challenges [22]. These activities encompass the conversion of waste into energy, the treatment of wastewater, and the regulation of the transportation of hazardous waste. The municipality also prioritizes educating the general public about the significance of waste sorting and recycling [22]. Ajman has achieved notable advancements, such as reducing the quantity of garbage sent to landfills after implementing the waste incinerator [22].

The Environmental Agency Abu Dhabi (EAD) was established in 1996 to protect groundwater, biodiversity, air quality, and ecosystems in Abu Dhabi, UAE, and is responsible for waste management in the region [23]. The EAD aims to advance environmental consciousness, facilitate sustainable progress, and guarantee environmental durability in accordance with the UAE's foremost objectives [23]. The tasks for waste management are distributed among three primary institutions: Tadweer oversees the management of municipal trash, commercial, medical, agricultural, industrial, and construction and demolition garbage [23]. The Abu Dhabi National Oil Company (ADNOC) is accountable for oil and gas waste, and the Federal Authority for Nuclear Regulation (FANR) is in charge of handling radioactive waste [23].

In addition, the Centre of Waste Management Abu Dhabi (CWM) and the Department of Municipal Affairs (DMA) provide support for waste reduction initiatives in Abu Dhabi [23]. Sharjah, UAE, employs an intricate waste management system that involves multiple steps and significant actors [34]. Bee'ah, an environmental company responsi-

ble for overseeing the collection, transportation, and processing of MSW, is tasked with managing the waste management plan of Sharjah [34]. Prior to being dispatched to a material recovery facility (MRF), refuse is gathered in compactors and conveyed to a transfer station, where it is temporarily held. Waste is placed on the tipping floor at the MRF and then transferred onto feeding conveyors for sorting [34]. This procedure aims to retrieve necessary secondary raw materials (SRM) by utilizing a combination of mechanical and manual sorting processes [34].

Despite the importance of understanding the KAP of waste segregation in improving both the environment and economy, there is a lack of research on the waste segregation of UAE population KAP regarding these matters. Accordingly, there is a need for more research studies to reduce this gap.

The current study aims to find the KAP regarding the waste segregation of individuals toward waste segregation in the UAE, thereby contributing to the development of sustainable waste segregation practices. The KAP of waste segregation research gave us a deep view of the current situation and it will help the country protect its environment and improve its economy by understanding the KAP of the population and taking action to improve it [35–37].

The current study aims to answer the following research questions:

RQ 1. What is the KAP level of the consequences of waste segregation in the UAE population, and how does it impact waste segregation in the UAE?

RQ 2. Is there any correlation between KAP and sociodemographic data in the UAE?

Similarly, the present study aims to verify the following research hypotheses:

H0. *KAP and sociodemographic data do not impact waste segregation in the UAE.*

H1. *There is a correlation between waste segregation in the UAE and factors of KAP, and sociodemographic characteristics.*

2. Materials and Methods

2.1. Study Design and Data Collection

Data were collected for the present descriptive analytical cross sectional study using a validated online questionnaire by UAEU Social Sciences Ethics Committee Research Number: ERSC_2024_4360, obtained on 9 March 2024. The questionnaire, built on previous articles, consisted of 15 items measured on a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). The sample population was determined using the G*Power version 3.1.9.6 program to be 385 [38], and the sample size was calculated based on the size of the UAE population [39].

The determined sample size was 385, as calculated by the G*Power program [38]. The online questionnaire was given randomly to 431 individuals. Participants willingly consented to complete it and had the option to withdraw from it at any point. The purpose of collecting these numbers was to prevent errors, and we achieved a response rate of 100%.

Subsequently, to ensure a broad representation of views on waste segregation, the inclusion standards of participants include volunteering and living in the UAE, and participants should be between 18 and 64 years old. Exclusion standards included participants less than 18 years old and visitors to UAE. The sample for this study was obtained via non probability sampling, resulting in a response rate comprising 84.1% females and 15.9% males. This demographic distribution supports our findings, indicating a correlation between waste segregation KAP and gender in the UAE. The overall Cronbach's alpha coefficient for the KAP questions was 0.891, indicating acceptable internal consistency and reliability of the study instrument.

The first part of the survey questionnaire has 10 control questions that will be used to record sociodemographic data; the rest of the questionnaire includes 15 questions developed to capture waste segregation divided into 5 knowledge questions (Table 1), which included questions about familiarity with waste segregation and sorting [10,21,39–41]; 5 attitude ques-

tions (Table 2) toward waste separation, sorting, and recycling will also be examined [4,10,41]. Furthermore, the other five practice questions (Table 3) determinants, such as practice toward waste segregation, will be investigated [4,10,41].

Table 1. Knowledge questions.

	Question	Reference
KQ 1	I know what waste segregation is.	[40]
KQ 2	I am aware of recycling or waste separation programs in the local municipality.	[21]
KQ 3	I know where to put my household waste after separation.	[41]
KQ 4	I am familiar with hazardous waste sorting.	[10]
KQ 5	I know what types of waste are recyclable.	[21]

Table 2. Attitude questions.

	Question	Reference
AQ 1	Waste sorting is effective in controlling environmental pollution.	[4]
AQ 2	I separate garbage by type and throw waste materials to the areas designed for them (glass, plastics, paper, organic or other) when it is available.	[21]
AQ 3	I think there is a relationship between education level and knowledge of waste management.	[4]
AQ 4	I think waste sorting can recycle resources.	[10]
AQ 5	Waste separation at my place is good for the environment.	[41]

Table 3. Practice questions.

	Question	Reference
PQ 1	I think it will do great harm to environment if I do not sort waste.	[10]
PQ 2	I recommend others to do waste sorting for recycling.	[4]
PQ 3	I use separate containers for waste sorting.	[4]
PQ 4	I think it will waste resources if I cannot sort waste properly.	[10]
PQ 5	I have practiced waste separation for some time.	[41]

2.2. Data Analysis Tools

The statistical analyses were carried out to evaluate and compare knowledge about plastics among participants. Data were collected, checked, revised, and organized in tables and figures using Microsoft Excel 2016. Normality was applied to check the data normality, whether parametric or nonparametric data, using the Shapiro–Wilk test and Kolmogorov–Smirnov at $p = 0.05$ level.

The nonparametric data were described statistically using both graphical and numerical descriptions. Parametric data were defined in terms of mean and standard deviation (SD). Nonparametric data were expressed in terms of frequency (n, %), mean, median, mode, quartiles (Q1, Q3), and SD. Inferential statistics in nonparametric data for comparing scores were performed using the Chi-square test for goodness-of-fit. However, inferential statistics of parametric data for comparing KAP were created using one way analysis of variance (ANOVA) at $p = 0.05$ level.

ANOVA was followed by Duncan's Multiple Range Test (DMRTs) at $p = 0.05$ level. The questionnaire reliability and internal consistency were assessed using Cronbach's alpha test at a probability level of 0.05. Three significance levels were proposed at $p = 0.05$ (*), at $p = 0.01$ (**), and $p = 0.001$ (***). Data analyses were conducted using the computer software Statistical Package for Social Science (SPSS), IBM-SPSS version. 29.0 for Mac OS [42]. The principal component analysis (PCA) was applied as a method for determining the weights in an index and identifying the underlying factors or components driving the variation in a dataset. PCA was performed using PAST statistical software version 4.0 [43].

3. Results

3.1. Sociodemographic Variables

The target sample size was 385. However, 431 were collected to avoid errors. Any respondents younger than 18 and outside the UAE were deleted. There were ten sociodemographic variables and 391 respondents in the UAE.

A notable majority (84.1%) of the participants were females, and (15.9%) were male; the gender difference was highly significant, as revealed by the Chi-square test. Most participants (67.0%) fall into the 18–24 age group; the representation decreased steadily in older age groups, with no participants over 65. The highest level of education reported was a Bachelor's degree (47.3%), followed by a high school degree or equivalent (43.2%).

Only a tiny percentage completed a master's (4.6%) or doctorate (1.8%). The parents' educational levels showed a relatively high level of education, with more than half having at least a high school degree or higher. The father's education level was found to be 67.2%, and the mother's education level was found to be 73.1%.

Interestingly, the mother's educational level was slightly higher on average than the father's. Most participants were students (58.8%), with a significant portion employed (25.1%), and unemployment was found to be 2.3%. The parent's employment status showed a high percentage of unemployed mothers (49.4%) compared to fathers (6.9%). In addition, a significant proportion of fathers were retired (25.3%), which was consistent with the age distribution of the sample (Figure 1) (Table 4).

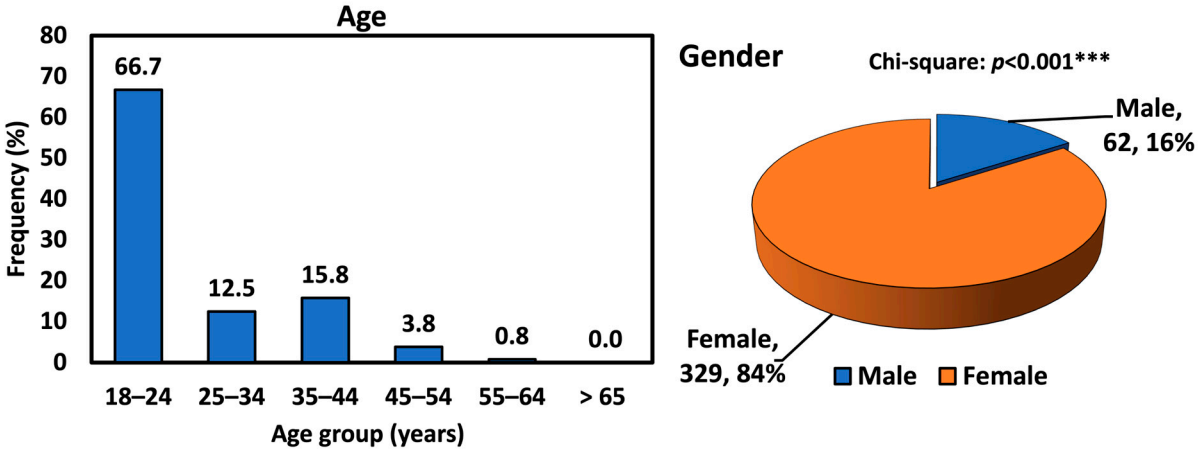


Figure 1. Distribution of participants according to age and gender. ***, highly significant at $p < 0.001$.

Table 4. Sociodemographic variables ($N = 391$).

Variables		Frequency		Chi-Square
		n	%	
Gender	Male	62	15.9%	<0.001 ***
	Female	329	84.1%	
Age	18–24 years old	262	67.0%	<0.001 ***
	25–34 years old	49	12.5%	
	35–44 years old	62	15.9%	
	45–54 years old	15	3.8%	
	55–64 years old	3	0.8%	
	Older than 65 years old	0	0%	
The highest level/degree of education	Less than high school	12	3.1%	<0.001 ***
	High school degree or equivalent	169	43.2%	
	Bachelor's degree (e.g., BA, BS)	185	47.3%	
	Master's degree (e.g., MA, MS, MEd)	18	4.6%	
	Doctorate (e.g., PhD, EdD)	7	1.8%	

Table 4. *Cont.*

Variables		Frequency		Chi-Square
		n	**%**	
Mother's education level	Less than high school	105	26.9%	<0.001 ***
	High school degree or equivalent	130	33.2%	
	Bachelor's degree (e.g., BA, BS)	136	34.8%	
	Master's degree (e.g., MA, MS, MEd)	15	3.8%	
	Doctorate (e.g., PhD, EdD)	5	1.3%	
Father's education level	Less than high school	107	27.4%	<0.001 ***
	High school degree or equivalent	115	29.4%	
	Bachelor's degree (e.g., BA, BS)	99	25.3%	
	Master's degree (e.g., MA, MS, MEd)	49	12.5%	
	Doctorate (e.g., PhD, EdD)	21	5.4%	
Current employment status	Other	9	2.3%	<0.001 ***
	Unemployed	48	12.3%	
	Student	230	58.8%	
	Retired	6	1.5%	
	Employed	98	25.1%	
Mother's current employment status	Other	54	13.8%	<0.001 ***
	Unemployed	193	49.4%	
	Student	6	1.5%	
	Retired	35	9.0%	
	Employed	103	26.3%	
Father's current employment status	Other	58	14.8%	<0.001 ***
	Unemployed	27	6.9%	
	Student	8	2.0%	
	Retired	99	25.3%	
	Employed	199	50.9%	

***, highly significant at $p < 0.001$. *N*, the total number of participants; *n*, the number of participants within each category; %, the percentage of participants in a category to the total.

3.2. Questionnaire Reliability and Internal Consistency

The Cronbach's alpha reliability coefficients for the scales of knowledge (five items), attitudes (five items), and practices (five items) were 0.78, 0.79, and 0.80, respectively, indicating high internal consistency within each scale.

The overall reliability for the combined 15 items was also high at 0.90. These results suggested that the scales were reliable tools for measuring the constructs of KAP, offering credibility to any findings derived from their use (Table 5).

Table 5. Reliability analysis.

ID	Scales	Number of Items	Cronbach's Alpha Reliability
1	Knowledge	5	0.78
2	Attitudes	5	0.79
3	Practices	5	0.80
Total		15	0.90

3.3. Normality

The Kolmogorov–Smirnov test revealed significant deviations from normality for the constructs of knowledge ($D(391) = 0.091$, $p < 0.001$), attitudes ($D(391) = 0.112$, $p < 0.001$), and practices ($D(391) = 0.096$, $p < 0.001$). Consistently, the Shapiro–Wilk test also indicated significant departures from normality for knowledge ($W(391) = 0.960$, $p < 0.001$), attitudes ($W(391) = 0.948$, $p < 0.001$), and practices ($W(391) = 0.955$, $p = 0.001$).

3.4. Descriptive Statistics of the Constructs

The respondents were asked to rate their agreement following a five-point Likert scale ranging from 1, strongly disagree, to 5, strongly agree.

The descriptive statistics of waste segregation KAP among 391 respondents showed that participants generally rated high on a five-point Likert scale. The mean ± SD scores indicated a positive orientation toward waste segregation, with knowledge (mean ± SD = 3.59 ± 0.78) above the midpoint, suggesting a moderate spread of responses among the sample who had poor knowledge (3.6%), fair knowledge (5.9%), good knowledge (31.5), very good knowledge (42.2%), and excellent knowledge (16.9%) (Figure 2).

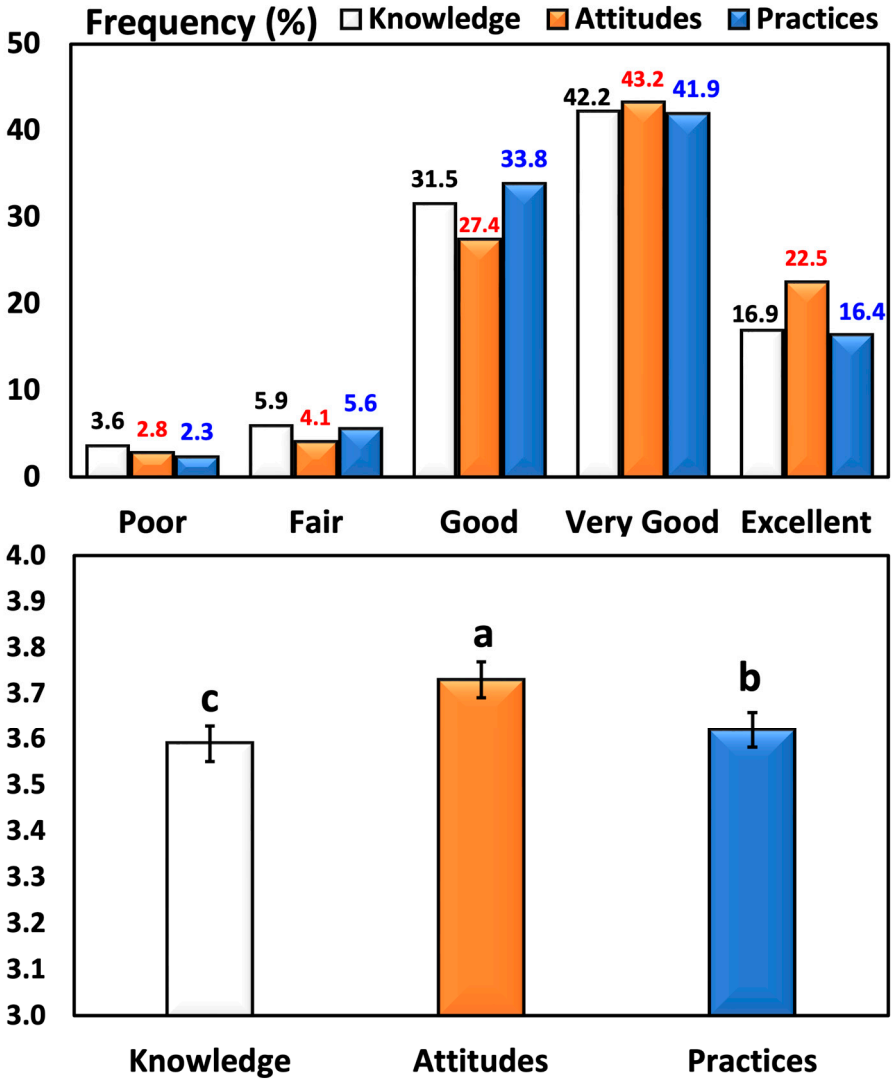


Figure 2. Description of overall scores for knowledge, attitude, and practice. According to Duncan's Multiple Range Test (DMRT), bars followed by different letters are significantly different at $p = 0.05$ significance level.

Attitudes (mean ± SD = 3.73 ± 0.77) above the midpoint also suggested a moderate spread of responses among the sample, which had poor attitudes (2.8%), fair attitudes (4.1%), good attitudes (27.4%), very good attitudes (43.2%), and excellent attitudes (22.5%) (Figure 2).

Practices (mean ± SD = 3.62 ± 0.76) were above the midpoint. Included in the sample were those who had poor practices (2.3%), fair practices (5.6%), good practices (33.8%), very good practices (41.9%), and excellent practices (16.4%) (Figure 2) (Tables 6 and 7).

Table 6. Descriptive statistics for knowledge, attitudes, and practices in terms of mean, median, mode, quartiles, and standard deviation (SD).

Variables	Mean	SD	Median	Mode	Percentiles		Chi-Square
					25	75	
Knowledge Q1	3.5	1.1	4.0	4.0	3.0	4.0	<0.001 ***
Knowledge Q2	3.6	1.1	4.0	4.0	3.0	4.0	<0.001 ***
Knowledge Q3	3.6	1.1	4.0	4.0	3.0	4.0	<0.001 ***
Knowledge Q4	3.6	1.1	4.0	4.0	3.0	4.0	<0.001 ***
Knowledge Q5	3.8	1.0	4.0	4.0	3.0	5.0	<0.001 ***
Knowledge (average)	3.6	0.8	3.6	3.0	3.0	4.0	<0.001 ***
Attitude Q1	4.0	1.0	4.0	4.0	3.0	5.0	<0.001 ***
Attitude Q2	3.6	1.1	4.0	4.0	3.0	4.0	<0.001 ***
Attitude Q3	3.5	1.1	4.0	4.0	3.0	4.0	<0.001 ***
Attitude Q4	3.9	0.9	4.0	4.0	3.0	5.0	<0.001 ***
Attitude Q5	3.8	1.0	4.0	4.0	3.0	5.0	<0.001 ***
Attitudes (average)	3.7	0.8	3.8	4.0	3.2	4.2	<0.001 ***
Practice Q1	3.7	1.1	4.0	4.0	3.0	5.0	<0.001 ***
Practice Q2	3.9	1.0	4.0	4.0	3.0	5.0	<0.001 ***
Practice Q3	3.3	1.1	3.0	3.0	3.0	4.0	<0.001 ***
Practice Q4	3.7	1.0	4.0	4.0	3.0	4.0	<0.001 ***
Practice Q5	3.6	1.0	4.0	4.0	3.0	4.0	<0.001 ***
Practices (average)	3.6	0.8	3.6	4.0	3.0	4.0	<0.001 ***

***, significant at $p < 0.001$; SD = standard deviation, Knowledge Q1-5 = knowledge questions, knowledge (average) = mean of total knowledge marks, Attitude Q1-5 = attitude questions, Attitudes (average) = mean of the total attuited points, Practice Q1-5 = practices questions, Practices (average) = mean of total practice marks.

Table 7. Descriptive statistics for knowledge, attitudes, and practice in terms of mean, median, mode, quartiles, and standard deviation (SD).

Variables	Strongly Disagree		Disagree		Neutral		Agree		Strongly Agree		Chi-Square
	n	%	*n*	%	*n*	%	*n*	%	*n*	%	
Knowledge Q1	31	7.9	32	8.2	121	30.9	134	34.3	73	18.7	<0.001 ***
Knowledge Q2	25	6.4	38	9.7	87	22.3	159	40.7	82	21.0	<0.001 ***
Knowledge Q3	22	5.6	36	9.2	107	27.4	155	39.6	71	18.2	<0.001 ***
Knowledge Q4	14	3.6	48	12.3	113	28.9	136	34.8	80	20.5	<0.001 ***
Knowledge Q5	12	3.1	26	6.6	89	22.8	165	42.2	99	25.3	<0.001 ***
Attitude Q1	17	4.3	15	3.8	72	18.4	153	39.1	134	34.3	<0.001 ***
Attitude Q2	18	4.6	43	11.0	106	27.1	139	35.5	85	21.7	<0.001 ***
Attitude Q3	26	6.6	48	12.3	105	26.9	148	37.9	64	16.4	<0.001 ***
Attitude Q4	10	2.6	13	3.3	81	20.7	186	47.6	101	25.8	<0.001 ***
Attitude Q5	17	4.3	23	5.9	90	23.0	152	38.9	109	27.9	<0.001 ***
Practice Q1	16	4.1	32	8.2	108	27.6	137	35.0	98	25.1	<0.001 ***
Practice Q2	12	3.1	19	4.9	87	22.3	159	40.7	114	29.2	<0.001 ***
Practice Q3	23	5.9	63	16.1	124	31.7	123	31.5	58	14.8	<0.001 ***
Practice Q4	12	3.1	24	6.1	122	31.2	151	38.6	82	21.0	<0.001 ***
Practice Q5	17	4.3	42	10.7	102	26.1	163	41.7	67	17.1	<0.001 ***

***, significant at $p < 0.001$, knowledge Q = knowledge questions, attitude Q = attitude questions, practice Q = practices questions, *n* = number of the participants in each category, % = percentage of participants.

3.5. Correlation Tests of Waste Segregation KAP and Sociodemographic Variables

The correlations of waste segregation KAP with sociodemographic variables revealed a positive relationship between gender and knowledge ($p < 0.001$), indicating a solid association where higher knowledge levels were linked with gender for waste segregation (Table 8). The correlation between attitudes and the mother's current employment status was negatively correlated (r = −0.101), indicating that the mother's current employment status does not affect more favorable attitudes toward waste segregation (Table 8).

Table 8. Spearman's correlations of waste segregation knowledge, attitudes, and practices with sociodemographic variables.

		Gender	Age	The Highest Level	Mother's Education Level	Father's Education Level	Employment	Mother's Employment	Father's Employment	Knowledge	Attitude
Knowledge	r	0.180	0.046	0.087	−0.035	−0.071	−0.012	−0.029	0.034	--	0.645
	p	0.002 **	0.364	0.086	0.487	0.163	0.812	0.571	0.503	--	<0.001 ***
Attitudes	r	0.118	0.056	0.024	−0.091	−0.082	−0.001	−0.085	−0.029	0.645	---
	p	0.019 *	0.267	0.634	0.071	0.106	0.986	0.095	0.574	<0.001 ***	---
Practices	r	0.097	0.086	0.065	−0.106	−0.027	0.011	−0.042	−0.04	0.663	0.708
	p	0.055	0.088	0.201	0.036 *	0.601	0.824	0.412	0.426	<0.001 ***	<0.001 ***

*, **, *** Correlation was significant at $p < 0.05$, $p < 0.01$, $p < 0.001$ (2-tailed); r, Spearman's correlation coefficient; *p*, two tailed significance test.

Knowledge and attitudes were positively correlated (r = 0.645, $p < 0.001$), indicating a solid association where higher knowledge levels were linked with more positive attitudes toward waste segregation. Similarly, knowledge and practices were significantly correlated (r = 0.663, $p < 0.001$), suggesting that increased knowledge about waste segregation was associated with more waste management practices (Table 8).

The correlation between attitudes and practices was also strong (r = 0.708, $p < 0.001$), indicating that more favorable attitudes toward waste segregation were associated with more waste management practices (Table 8). These significant correlations at the 0.01 level (2-tailed) suggested a robust interrelationship among KAP related to waste segregation, highlighting the interconnectedness of these constructs in the context of waste segregation (Table 8).

Table 9 represents the results of logistic regression for the effect of gender, age, educational level (participants, mothers, fathers), and employment status (participants, fathers, mothers) on average KAP scores. According to logistic regression, gender has a highly significant effect ($p < 0.001$ ***) on knowledge and practice and a nonsignificant effect on attitudes (Table 9).

Table 9. Logistic regression for the effect of gender, age, educational level (participants, mothers, fathers), and employment status (participants, fathers, mothers) on average knowledge, attitude, and practice scores.

Effect	Knowledge		Attitude		Practice	
	Chi-Square	*p* Value	Chi-Square	*p* Value	Chi-Square	*p* Value
Gender	4605.8	<0.001 ***	18.0	0.525 ns	208.1	<0.001 ***
Age	21,766.5	<0.001 ***	61.5	0.886 ns	96.3	0.058 ns
The highest level/degree of education	31.1	0.039 *	14.9	0.731 ns	160,868.5	<0.001 ***
Mother's education level	17.6	0.552 ns	21.4	0.315 ns	149.0	<0.001 ***
Father's education level	467.6	<0.001 ***	26.2	0.125 ns	240.1	<0.001 ***
Current employment status	12.9	0.844 ns	21.5	0.310 ns	1571.3	<0.001 ***
Mother's current employment status	193.4	<0.001 ***	24.6	0.175 ns	398.9	<0.001 ***
Father's current employment status	28.9	0.068 ns	87.9	0.166 ns	456.1	<0.001 ***

*, significant at $p < 0.05$; ***, highly significant at $p < 0.001$; ns, nonsignificant at $p > 0.05$.

Age had a highly significant effect ($p < 0.001$ ***) on knowledge and a nonsignificant effect on attitudes and practice. The highest educational level of participants had a significant effect on both knowledge ($p = 0.039$ *) and practice ($p < 0.001$ ***) and nonsignificant effect on attitudes (Table 9). Generally, gender, the highest educational level, the father's educational level, and the mother's employment status significantly affected practice. However, all sociodemographic parameters had a nonsignificant impact on attitude (Table 9).

In addition, gender, the highest educational level, the mother's and father's educational level, current employment status, the mother's employment status, and the father's employment status significantly affected practices (Table 9).

3.6. Regression of Waste Segregation Practice on Attitudes and Knowledge

The regression analysis demonstrated a significant and impactful relationship between KAP and waste segregation. The results highlighted the importance of knowledge and attitudes in influencing practices, with attitudes having a slightly more pronounced effect.

The model summary (Table 10) shows that the predictors, knowledge, and attitudes strongly correlate with practices (R = 0.783), indicating a relationship. The R square value of 0.613 suggested that 61.3% of the variance in practices was explained by the model, a substantial proportion. The adjusted R square, at 0.611, adjusts this value slightly for the number of predictors but still indicates a significant explanatory power. The Durbin–Watson statistic of 2.019 pointed to a moderate level of autocorrelation in the residuals, which was within the acceptable limits and did not detract from the model's validity.

Table 10. Waste segregation practice model summary [a].

Model	R	R^2	Adj. R^2	SE	Change Statistics					Durbin-Watson
					R^2 Change	F-Change	df_1	df_2	*p* Value	
1	0.783 [b]	0.613	0.611	0.47931	0.613	307.04	2	388	0.001 ***	2.019

[a] Independent variables (predictors): constant, attitudes, knowledge. [b] Dependent variable: practices. ***, highly significant at $p < 0.001$. R, correlation coefficient (0, no correlation; 0.1–0.3 weak correlation, 0.31–0.60 moderate correlation; >0.60 strong correlation); R^2, the coefficient of determination; Adj.R^2, is the determination coefficient adjusted for the number of independent variables; SE, standard error; R^2 change, the change in R^2; F-change, the change in F-ratio; df1, degree of freedom for variables (=number of independent variables); df2, degree of freedom in number of participants (=denominator degrees of freedom); Durbin-Watson statistic is a test for autocorrelation.

The ANOVA results (Table 11) further confirmed the model's effectiveness. The regression model was statistically significant ($F(2, 388) = 307.038$, $p < 0.001$), demonstrating a strong relationship between the independent variables (knowledge and attitudes) and the dependent variable (practices). The division of total variance into regression (141.077) and residual (89.139) parts underlined the model's capacity to account for significant practice variability.

Table 11. Waste segregation practices ANOVA [a].

Model		SS	df	MS	F-Ratio	*p* Value
1	Regression	141.08	2	70.54	307.04	0.001 [b]
	Residual	89.14	388	0.23		
	Total	230.21	390			

[a] Dependent variable (practices). ANOVA, analysis of variance; [b] Independent variable (predictors: constant, attitudes, and knowledge). SS, sum of square; df, degree of freedom; MS, mean squares.

The coefficients table (Table 12) provides detailed insights into the individual predictors. Both knowledge and attitudes are significant predictors of practices, with knowledge having a positive effect (B = 0.330, t = 8.013, $p < 0.001$) and a moderate influence (standardized Beta = 0.339) (Table 12). Attitudes showed a more substantial positive effect on practices (B = 0.513, t = 12.156, $p < 0.001$), with a higher Beta value of 0.515, indicating a more substantial impact on practices (Table 12). The collinearity statistics for both predictors are within acceptable ranges, suggesting that multicollinearity was not a concern in this model.

Table 12. Waste segregation practice coefficients [a].

Model		Unstandardized Coefficients		Standardized Coefficients	t	*p* Value	Collinearity Statistics	
		B	SE	Beta			Tolerance	VIF
1	(Constant)	0.524	0.128		4.104	0.001 ***		
	Knowledge	0.330	0.041	0.339	8.013	0.001 ***	0.556	1.797
	Attitudes	0.513	0.042	0.515	12.156	0.001 ***	0.556	1.797

[a] Dependent variable (practices). ***, highly significant at $p < 0.001$. SE, standard error; VIF, variance inflation factor; t, t-statistics.

Figure 3 represents a red–blue heatmap presenting the interrelationship between study variables. Red indicates a negative correlation, blue indicates a positive correlation, and white indicates no correlation. The two-tailed significance test revealed the boxed colors for significant correlation. According to the heatmap, a significant positive correlation exists between participants' educational level and total knowledge scores (Figure 3).

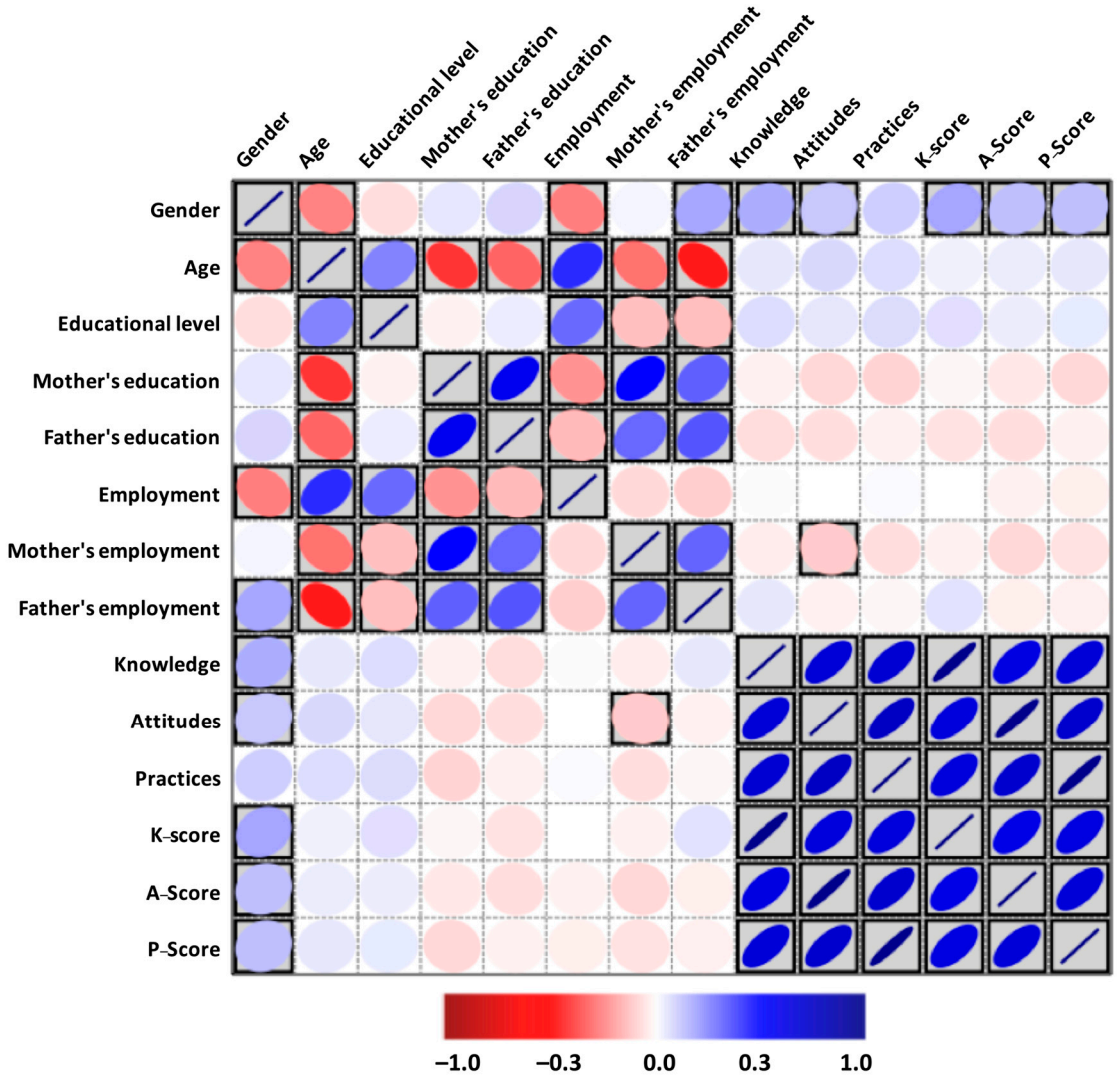


Figure 3. Red and blue heat maps present the interrelationship between study variables. Color intensity corresponds to correlation strength, blue color indicates positive correlation, red boxes indicate negative correlation, and grey-boxed colors for significant correlation according to a two-tailed significance test. K-score = knowledge score; A-score = attitude score; and P-score = practices score.

There was a significant positive correlation between KAP. In addition, there was a significant positive correlation between knowledge scores, attitudes, and practices (Figure 3).

Figure 4 summarizes the effect of the main study variables on participants' responses. The two axes, PCA-1, and PCA-2, represented 25.5% and 24.33% of total study variables. The shaded area represented 95% confidence. The PCA ordination revealed a marked effect on educational level, father's educational level, and mother's educational level, which appear in the upper right of the PCA (Figure 4).

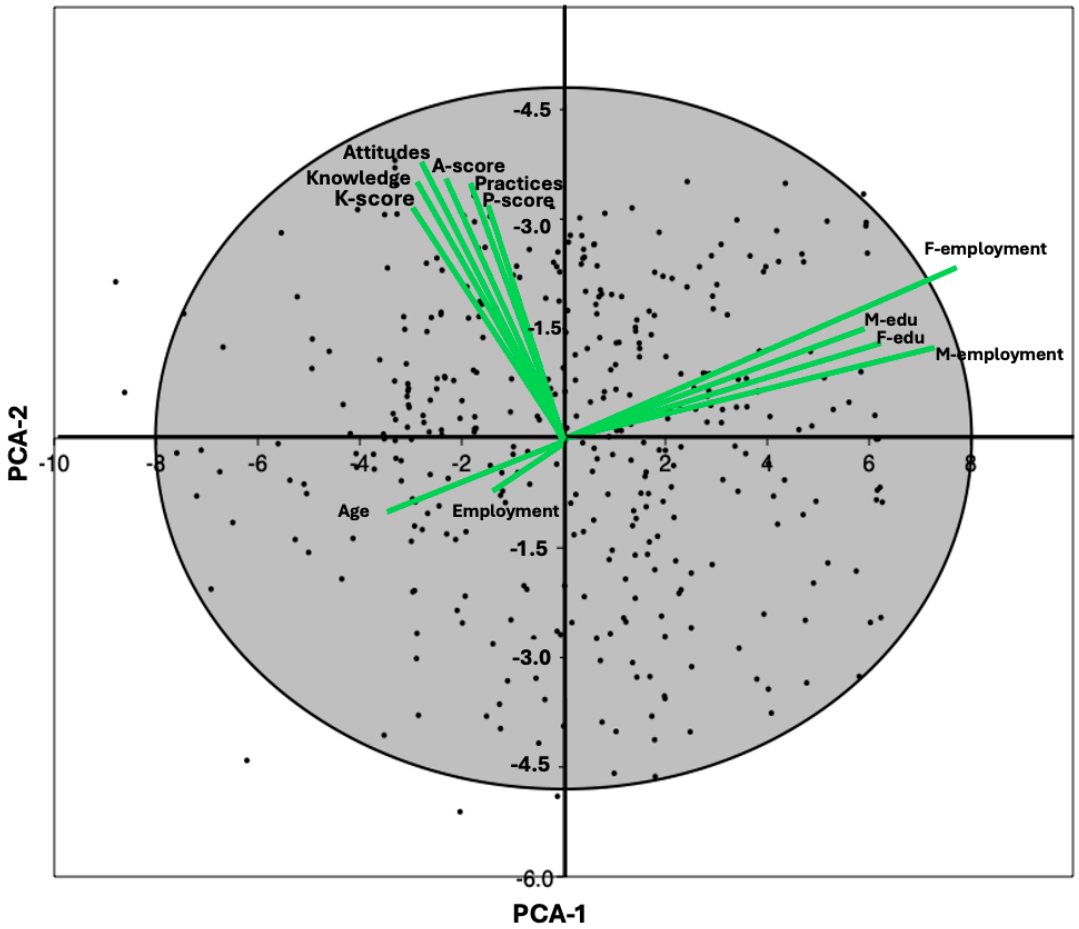


Figure 4. Principal component analysis (PCA) ordination presents the interrelationship between study variables. PCA-1, and PCA-2 represent PCA axes 1, and 2.

4. Discussion

In Northwest Ethiopia, Deress et al. [44] demonstrated a correlation between knowledge with attitudes, knowledge with practices, and attitudes with practices [44]. Our findings in the current study showed a significant moderate correlation between attitude and practices (r = 0.741, $p < 0.001$), indicating that more favorable attitudes toward waste segregation were associated with more waste management practices. Moreover, there was a positive correlation between knowledge and attitude (r = 0.666, $p < 0.001$) and a positive correlation between knowledge and practices (r = 0.682, $p < 0.001$) in the present study.

A significant proportion of participants in the study conducted by Badrum and bin Mapa [45] in Penampang Proper Village, Sabah, Malaysia, demonstrated a strong knowledge, a positive attitude, and effective practice of solid waste management practices KAP. While the level of knowledge and attitude was typically high, the study revealed no statistically significant relationship between them and the actual practices [45]. The practice level of waste management was shown to be substantially connected with two sociodemographic variables: year of birth and levels of education. This suggests that individuals who are

younger and more educated are likely to have a higher predisposition to engage in better waste management practices [45].

Furthermore, Badrum and bin Mapa's [45] study revealed a direct relationship between knowledge and attitude, suggesting that individuals with greater levels of education are more inclined to hold good attitudes about trash management [45]. Similarly to our findings, there was a positive correlation between knowledge and practices. Moreover, the current study revealed a positive correlation (r = 0.159, $p < 0.001$) between general waste segregation KAP and sociodemographic variables. This indicates a strong association, suggesting that higher levels of knowledge are linked to gender concerning waste segregation. In addition, there was a significant correlation (r = 0.110) between attitude and gender, indicating that gender was associated with increased knowledge about waste segregation.

In Vietnam, Giao and Thien [46] analyzed waste composition and community KAP to evaluate the elements that impact KAP in domestic solid waste management. The goal was to create a comprehensive plan for effective domestic waste management. The Chi-square test demonstrated a statistically significant correlation between the KAP level of the participants and demographic characteristics ($p < 0.05$). The key characteristics that exerted a substantial influence were the amount of education and age [46]. The current study reported a significant positive association (r = 0.159, $p < 0.001$) between KAP related to general waste segregation and sociodemographic characteristics. This suggests a robust correlation, indicating a connection between higher levels of knowledge and gender regarding waste segregation.

In addition, a separate study conducted in Nakuru town, Kenya, by Kamweru [47] examined various types of solid waste generated by families, assessed residents' attitudes toward existing solid waste management systems, and ascertained the levels of KAP among households and authorities. Unfavorable practices were witnessed, such as the random disposal of waste in exposed locations and drainage channels, as well as the burning and burial of solid waste in dug-out pits. The cross-tabulation analysis revealed a substantial impact of respondents' age on attitudes toward solid waste management operations ($p < 0.001$). Kamweru's [47] study also found a strong link ($p < 0.001$) between the educational attainment of residents and their behavior toward solid waste management [47]. The analysis in the current study revealed a noteworthy correlation (r = 0.110) between attitude and gender, suggesting that gender was linked to a higher level of understanding regarding segregation. Moreover, there was a negative connection (r = -0.101, $p < 0.001$) between attitudes and the mother's present employment situation.

5. Conclusions

This study highlights the critical relationship between KAP and waste segregation among UAE residents. The data demonstrated substantial correlations that indicated present behaviors and emphasized possibilities for policy interventions and educational programs designed to improve waste management practices.

In the current study, the KAP level of the consequences of waste segregation in the UAE population was as follows. knowledge (mean $\pm$ SD = 3.59 $\pm$ 0.78)—among the sample, ratings were as follows: those who had poor knowledge (3.6%), fair knowledge (5.9%), good knowledge (31.5), very good knowledge (42.2%), and excellent knowledge (16.9%); attitudes (mean $\pm$ SD = 3.73 $\pm$ 0.77)—among the sample, ratings were as follows: those who had poor attitudes (2.8%), fair attitudes (4.1%), good attitudes (27.4%), very good attitudes (43.2%), and excellent attitudes (22.5%); and practices (mean $\pm$ SD = 3.62 $\pm$ 0.76)—among the sample, ratings were as follows: those who had poor practices (2.3%), fair practices (5.6%), good practices (33.8%), very good practices (41.9%), and excellent practices (16.4%).

Furthermore, the present study demonstrated a positive correlation between knowledge and attitude (r = 0.666, $p < 0.001$) and a positive correlation between knowledge and practices (r = 0.682, $p < 0.001$), and this answered our research question 1. Also, there was a positive correlation (r = 0.159, $p < 0.001$) between general waste segregation KAP and sociodemographic variables, in which there was a significant correlation (r = 0.110) between

attitude and gender and a negative correlation ($r = -0.101$, $p < 0.001$) between attitudes and the current employment status of the mother. This answered research question 2 and proved H_1 was correct, which is that the sociodemographic impact of KAP and regret H0 do not affect each other.

Long-term monitoring and evaluation are crucial for ensuring the continued success of waste segregation initiatives. Implementing robust systems for ongoing monitoring and evaluation of these programs will enable stakeholders to monitor important metrics, such as waste diversion rates, public awareness, and changes in attitudes toward waste management. These metrics are crucial for evaluating the efficiency of implemented strategies and identifying areas that need additional improvement or support.

Future endeavors should prioritize broadening the research scope to encompass a wide range of demographic segments, thus facilitating the development of more customized and efficient waste management strategies. Systematic evaluation and education intervention will be crucial in achieving the UAE's sustainability goals and promoting responsible waste management by facilitating continuous adaptation and improvement.

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The Green Indium Patented Technology SCRIPT, for Indium Recovery from Liquid Crystal Displays: Bench Scale Validation Driven by Sustainability Assessment

Alessandro Becci, Alessia Amato, Giulia Merli and Francesca Beolchini *

Department of Life and Environmental Sciences, Polytechnic University of Marche, 60131 Ancona, Italy; a.becci@univpm.it (A.B.); a.amato@univpm.it (A.A.); g.merli@univpm.it (G.M.)
* Correspondence: f.beolchini@univpm.it

Abstract: Indium is considered a valuable and irreplaceable material for a variety of applications that improve the quality of human life. Due to its limited availability and the growing demand, it is mandatory to find sustainable solutions for indium recovery from end-of-life devices. The green indium patented technology SCRIPT (ITA202018000008207) focuses on recovering indium from ground LCD panels, developed through laboratory scale investigation. The process ensures high recovery efficiencies of indium (>90%), features a simple design, and fully exploits the solid residue with the production of a concrete for building applications. This manuscript presents a study focused on the validation and optimization of the patented SCRIPT technology at the bench scale, driven by sustainability assessment. Bench scale experiments successfully validated the technology, improving its technology readiness level. Furthermore, an environmental sustainability assessment highlighted the importance of treating the finest fraction, which has the highest indium concentration. Optimization tests at the bench scale demonstrated that water could be recirculated for more than five cycles. The economic sustainability tests highlighted that when the indium concentration in the material fed into the recycling plant is above 1000 mg/kg, the technology is cost effective and worth investment. Our study is fundamental for boosting indium recycling in the world. Moreover, our methodological approach represents a guideline for achieving sustainability goals within circular economy approaches for strategic metals in complex matrices.

Keywords: indium; sustainability; bench scale; hydrometallurgy; patent

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1. Introduction

Indium is a valuable and irreplaceable material, especially in the technological sector, due to its several applications that contribute to improving the quality of human life [1,2]. In the electronics industry, indium is mainly used to produce liquid crystal displays (LCDs), where it is present as indium-tin oxide (ITO) on the surface of the glass substrates that contain liquid crystals [3–5]. Additionally, indium is used in photovoltaic cells (PVs), LEDs, batteries, and other applications [1].

Despite its economic value, indium is relatively scarce in both continental and oceanic crusts, with an abundance ranging between 0.05 and 0.072 mg/kg [6,7]. Currently, there are no specific ores for this metal and its primary production is mainly linked to the mining of sphalerite ores, copper sulphide (chalcopyrite) ores, and tin ores, where indium concentrations are typically below 20 mg/kg [2,7–9].

The global indium supply is under pressure due to its limited availability and growing demand [7]. Therefore, the recycling of indium from waste electrical and electronic equipment (WEEE) has become an important strategy worldwide to address this challenge [5]. In this perspective, one common method for secondary indium production is ITO recycling after the sputtering phase [2,5,6]. LCD scraps offer an interesting alternative, as they contain higher indium concentration than ores [6–9] and they are widely available, due to the

short lifecycle of devices [8–11]. The recycling of LCDs may reduce the high environmental impacts resulting from their conventional management (landfills, incinerators) and allows for resource conservation by reducing the need for primary production [12].

Several studies focused on the development of new technologies for the recovery of indium from WEEE residues [13]. These technologies promise lower energy consumption, reduced operational costs, and improved environmental sustainability, compared to traditional pyrometallurgical processes [7].

Most hydrometallurgical techniques for indium leaching from spent LCDs are based on strong mineral acids, such as hydrochloric acid, sulfuric acid, and nitric acid [6,14–23]. During acid leaching, the ITO layer is dissolved, releasing In(III) and Sn(IV) cations in the solution. The main reactions involved when ITO is treated with H_2SO_4 are shown in Equations (1) and (2) [17]. Indium is dissolved into the solution as indium ions (In^{3+}) (Equation (1)),

$$In_2O_3 + 3H_2SO_4 \rightarrow 2In^{3+} + 3{SO_4}^{2-} + 3H_2O \quad (1)$$

while tin is dissolved as follows (Equation (2)):

$$SnO_2 + 2H_2SO_4 \rightarrow Sn^{4+} + 2{SO_4}^{2-} + 2H_2O \quad (2)$$

In more detail, the leaching process begins when H_2SO_4 reacts with the surface of ITO glass, dissociating into ${SO_4}^{2-}$ and H^+ ions. This leads to the breakdown of the In-O bond, forming an intermediate In-O-H complex. The reaction proceeds until In^{3+} and ${SO_4}^{2-}$ are fully generated in the leaching solution [17].

Several studies focused on the optimization and enhancement of the acid leaching process by different lixiviant combinations [21]. In this regard, organic acids, such as oxalic, malic, or citric acid, were found to be effective leaching agents [24–26]. In some works, oxidizing and reducing chemical agents have been added in the acid leaching process to accelerate the reaction [26–29].

Another promising approach is bioleaching, promoted by microorganisms such as *Acidithiobacillus ferrooxidans*, *Acidithiobacillus thiooxidans*, and *Aspergillus niger*. This technique is promising for lower costs and higher sustainability terms, though research on this topic remains limited [30–34].

Furthermore, several methods were tested to recover indium from leach liquors produced by the mentioned techniques. Solvent extraction is the most common technique [13], while possible alternatives are represented by ionic liquid, nonvolatile and nonflammable, and sorbent, including ion exchange and chelating resins, extraction [7,9]. Another less common approach, used as highly effective recovery technique, is cementation, based on the differences in the electrochemical potentials of indium, compared to other elements [5]. This technique shows the advantages of a simple implementation, relatively low cost and toxicity (compared to the most common solvent extraction), and high ensured efficiency.

Much of the scientific literature only focuses on technical feasibility; however, in the current era, it is crucial also to consider the combination of effectiveness and sustainability of the developed approaches. From the results achieved through laboratory scale investigation, documented by several scientific publications [9,11,12,35], we developed the SCRIPT (*circular strategies for indium recovery from ground panels*) patent (ITA202018000008207), which ensures high indium recovery efficiencies (>90%). This process also features a simple treatment design and allows the exploitation of the whole solid residue with the production of a concrete for building applications. The goal of the present paper is to present a study focused on scaling up the patented SCRIPT technology to a bench scale level, driven by sustainability assessment. An integrated assessment is essential to ensure the development of viable solutions, given the relatively low indium concentration in solid waste (order of magnitude 10–1000 mg/kg). Moreover, the study includes: 1. the initial validation of the technology at bench scale level; 2. an environmental assessment finalized to identify the potential process configuration able to promote the process sustainability; 3. the further

experimental optimization to reduce the environmental impact; 4. and a final assessment that considers economic sustainability as well.

2. Materials and Methods

2.1. Samples

An SME recycler in Central Italy supplied the samples for bench scale experiments. The industrial facility collects and treats (by physical–mechanical treatment) around 30 tons of waste from WEEE, every day. The SME supplied to the Polytechnic University of Marche about 50 kg of crushed LCD panels (<10 cm), collected in big boxes and transported in plastic bags to university labs. The procedure reported below was implemented to achieve representative samples. A portion (4.820 kg) was placed on a clean table to form a cake with 7 cm thickness and 50 cm diameter (Figure 1); the cake was divided into 4 sections, and 2 of these fractions were selected to prepare a second cake with 3 cm thickness and 50 cm of diameter.



Figure 1. Waste supplied by a SME recycler in Central Italy.

At the end, the sample for the characterizations had a weight of 1154 kg; it was sieved to achieve 3 representative fractions: >5 mm, 1–5 mm, <1 mm. Chemical characterizations were performed by ICP-MS to quantify In and Ga concentrations.

2.2. The Bench Scale Experimental System

The leaching system consisted of three main components: a hot plate (Stuart SC162, Essex, UK), a 5 L jacketed reactor (the reactor is not a commercial product, but it was designed in the laboratory), and a peristaltic pump (Velp Scientifica™ SP 311, Usmate Velate, Italy) to ensure hot water circulation (Figure 2). More in detail, hot water, at 100 °C (used for both the leaching and cementation processes), was produced in a 2 L beaker placed on the hot plate and supplied to the reactor jacket with a 200 mL/min flow. The solution in the reactor reaches the requested temperature for leaching after 2 h (75–80 °C) and after 1 h (50–55 °C) for cementation. Thereafter, the hot water flows back from the jacketed reactor to the beaker, ensuring temperature maintenance (Figure 2).

At the end of each step, the leaching or cementation solution was pumped to the filtration system which includes the following: a peristaltic pump, a filtration system with a paper filter, and a vacuum pump (Chemker 400, New Taipei City, Taiwan). More in detail, the solution is pumped by the peristaltic pump at 240 mL/min flow (Figure 3) to the filtration system. The vacuum pump was used to promote and speed up the filtration operations. A total of 30 min was enough for the complete solution to be pumped from the reactor.

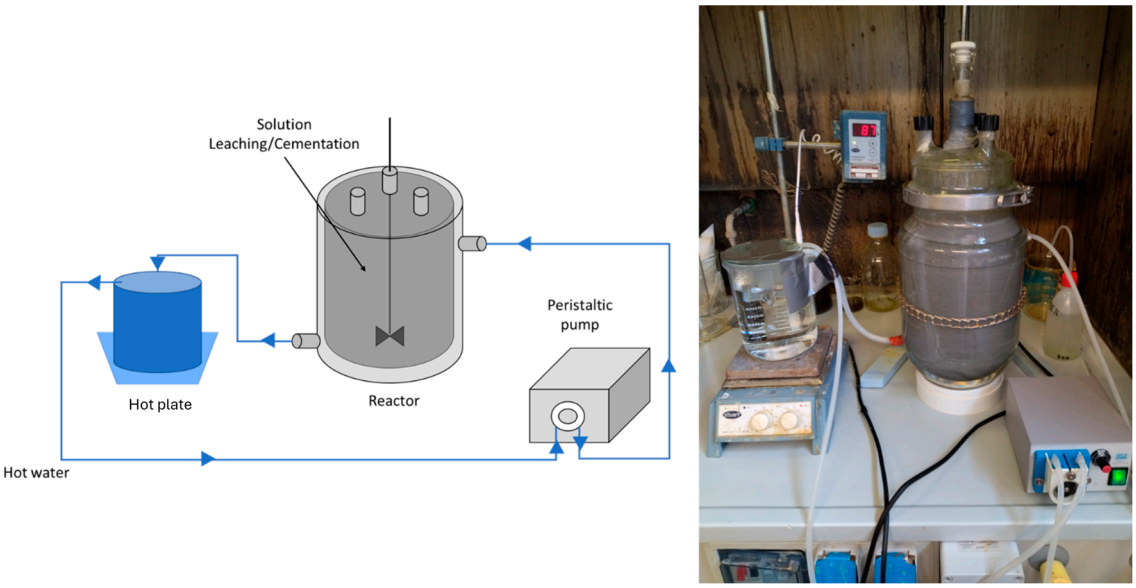


Figure 2. Schematic representation of the leaching and cementation process and the related photo.

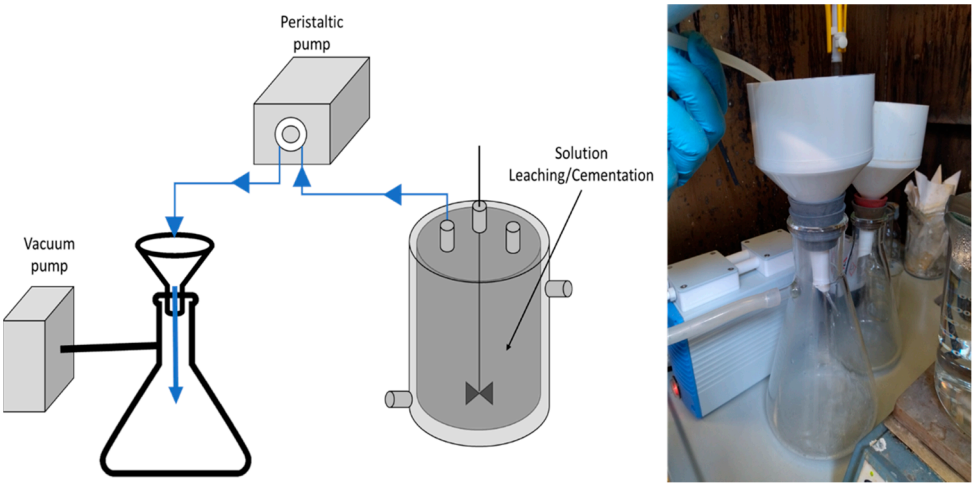


Figure 3. Schematic representation of the filter apparatus and the related photo.

2.3. Assessment of the Advantageous Process Configuration through the Life Cycle Methodology

Considering the relatively low indium concentration in the solid, the assessment considered the possibility of treating only the richest fraction using the patented SCRIPT technology and valorizing the other one through building material production, without the previous indium recovery.

The functional unit selected for the comparison is a complete treatment (pre-treatment, 3 leaching steps, and recovery) performed in a 5 L bench scale plant. The present analysis includes the results of inventory analysis, classification and characterization (mandatory), and normalization and weighting (optional) phases. The software used for data collection is Thinkstep Gabi Professional, combined with the Database for Life Cycle Engineering (compilation 7.3.3.153; DB version 6.115). The method selected for the analysis is EF 3.0, which includes all the environmental categories and recommended models at midpoint, together with their indicators, units, and sources [36]. Figure 4 represents the system boundaries considered for the analysis, which include 2 pre-treatment scenarios:

- Scenario 1: waste from recycler, with an average In concentration around 40 ppm, is crushed and sent to the patented technology SCRIPT.

- Scenario 2: waste from recycler facility is sieved and only the finest fraction (<1 mm) with the highest In concentration (157 ppm) is sent to the patented technology SCRIPT. The <1 mm fraction represents about 17% of the waste; therefore, 18 kg of LCDs are sieved to separate 3 kg, necessary for the 3-step process. The remaining 83% can be crushed and mixed with the scraps for building material production. This option allows an In pre-concentration in the waste flow but also metal loss in the >1 mm fraction (with an In content around 15 ppm).

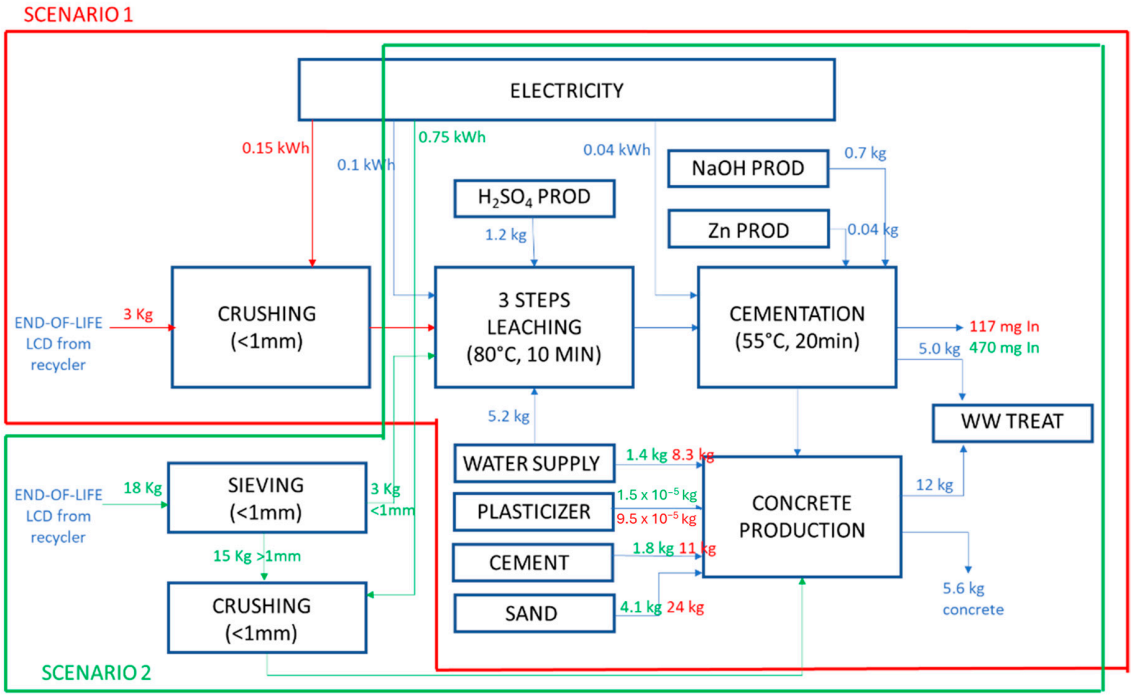


Figure 4. System boundaries considered for the LCA (Functional unit, a whole treatment of end-of-life LCD in the 5 L reactor). The red quantities are referred to scenario 1, green quantities to scenario 2, blue quantities are common to both scenarios.

Further leaching and cementation steps follow the conditions described in the bench scale validation section. For the quantification of the electricity impact, a European electricity grid mix (which includes both renewable and not-renewable energy resources) is selected. Some assumptions have been performed for the analysis:

- An environmental credit due to the avoided disposal in landfilling site has been included considering the current classification of end-of-life LCD panels as urban waste.
- The environmental credit related to the recovered In has been estimated by the allocation of Zn metal value on economic basis (240 USD/kg for In vs. 4 USD/kg for Zn). This assumption was considered acceptable since the two elements are extracted from the same ore, sphalerite [37].

2.4. Optimization of the Patented SCRIPT Technology at Bench Scale

The optimization of the patented technology SCRIPT is driven by the sustainability assessment (Section 2.3), and it includes the wastewater recirculation system. Figure 5 reports the whole scheme of the process. Fixed conditions were selected considering the results previously achieved: use of the finest LCD fraction (<1 mm) to increase In concentration, a 3 step cross-current leaching process, cementation with 7.5 g/L of Zn, and a water/treated LCD wet ratio of 2:1 to remove chlorides and sulphates for concrete production [35]. Starting from these conditions, wastewater recirculation from both cementation and LCD washing (before concrete production) was studied to improve sustainability in the process.

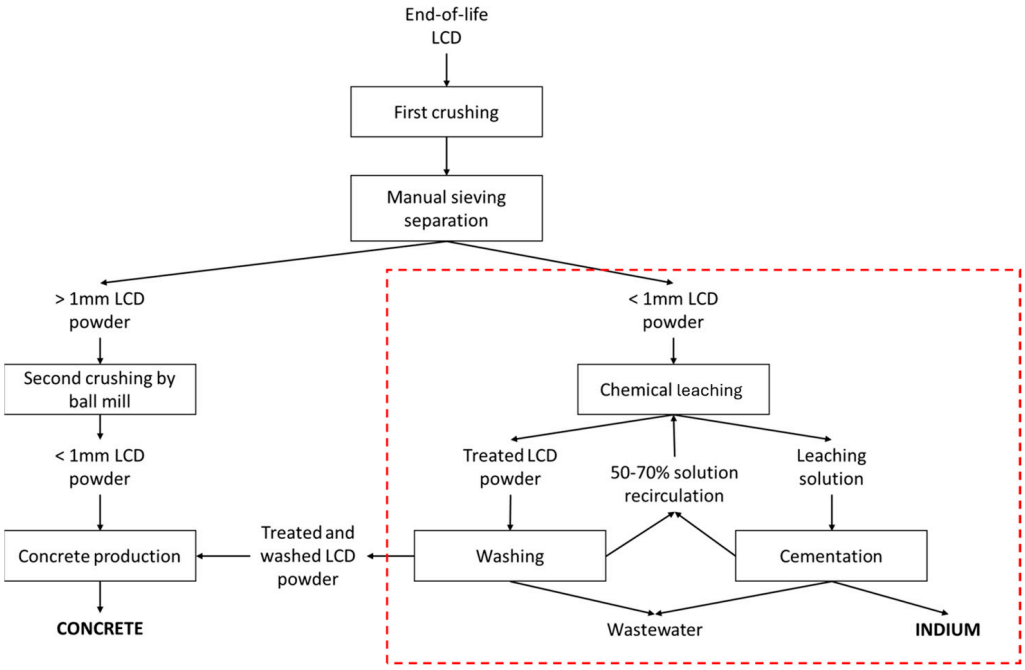


Figure 5. Schematic representation of the whole patent IT201800008207A1 process. The red box includes the process steps.

In the first process cycle, leaching and cementation processes were carried out using only the finest fraction (<1 mm) of the sample. On the other hand, from the second cycle, the 2M leaching solution was composed of the following: 50% of solution after the cementation process, 44.5% of solution after the treated LCD washing step, and 5.5% of H_2SO_4 solution (96% *v*/*v*). After the first step of the cross-current leaching, 10% of the leaching solution (lost for both evaporation phenomena and filtration steps) was restored by a fresh solution of 2M H_2SO_4 produced by the wastewater from the washing process.

2.5. The Economic Assessment

Table 1 summarizes the updated unitary costs considered for the evaluation, including the price of the panel management, if disposed of as urban waste (after the preliminary removal of hazardous components).

Table 1. Unitary costs considered for economic estimation.

Flow	Unitary Cost (EUR/kg)
Electricity (EUR/kWh)	0.1
NaOH	1
H_2SO_4	0.5
Zn	10
Wastewater treatment and disposal	0.1
Solid waste disposal	0.25
In	400

3. Results and Discussion

3.1. Sample Characterizations

Table 2 presents the results of ICP-MS analysis, highlighting variations in indium concentrations based on sample sizes. Indium concentrations ranged from 2.5 ± 0.5 mg/kg, in the biggest fraction, to 160 ± 30 mg/kg in the smallest one, while gallium showed a more uniform distribution. These results confirm the observations of previous studies, which observed a decrease in indium concentration with the fragment dimension increase [12,29].

However, the size of the smallest fraction is not constant in all the works, depending on the different grinding methods, and it varies between 10 μm and 212 μm [19,21,23]. Given the high variability of the fractions used in the literature, the analysis of the correlation between particle size and indium concentrations was worthy of investigation.

Table 2. Chemical characterization of three representative fractions of the crushed LCD panel.

<1	1 < Ø < 5	>5
	S1	
		

Waste	Dimension (mm)	Metal Conc. (mg/kg)	
		In	Ga
S1	<1	160 ± 30	6 ± 1
	1 < Ø < 5	17 ± 5	6 ± 3
	>5	2.5 ± 0.5	14 ± 2

Additionally, LCD composition is not homogeneous and can vary depending on the different production processes used (e.g., different brands), which explains the variable indium and other metal concentrations reported in the literature. Regardless of this aspect, all studies identify indium as the primary component of ITO, with higher content than the other metals [22]. Table 3 summarizes the indium concentrations measured in several works, along with the indication of other metals detected in the LCD panels. The variability related to the manufacturing peculiarities is in an acceptable range.

Table 3. Summary of indium content in LCD panels (mg/kg) from literature data.

Indium Content	Other Metals	Reference
100	Al, Ca, Fe, Mn, Mo, and Sn	[12]
261	Sn	[22]
576	Si, Al, B, Ca, Sr, Fe, Mg, Ba, Sn, Cr, Na, K, and Cu	[23]
120	Al, Fe, In, Ca, Mg, Sr, and Mo	[15]
30	n.a. [a]	[21]
n.a. [a]	Sn, Cu, Pb, and Al	[33]
219	Sn	[10]

[a] Not available.

3.2. Validation of the Patented SCRIPT Technology at Bench Scale

Figure 6 shows the indium concentration achieved at the end of each stage of the cross-current leaching process, along with the concentration of three main interferents: Fe, Al, and Cu. The results confirmed those previously observed at the lab scale [12] and during the development of the SCRIPT patent. Regardless of the process scale-up, an almost complete In extraction was achieved across the three leaching steps, with moderate extraction of the interferents. Al, Fe, and Cu were extracted with efficiencies of 12%, 5%, and 1%, respectively (Figure 6b). The tests also showed a volume loss around 10% due to evaporation phenomena and filtration steps. Therefore, the volume was restored by a fresh solution of 2M H_2SO_4, before the second and the third steps. The leaching solution

from the third step of the cross-current process was used to determine the best operative conditions for In recovery by cementation with Zn. As showed in Figure 7, In recovery showed efficiencies higher than 90% with a Zn concentration above 7.5 g/L. However, even Cu and Al exhibited recovery efficiency greater than 90% with Zn concentrations over 5 and 10 g/L, respectively. On the other hand, Fe recovery remained at around 20%, regardless of the Zn concentration.

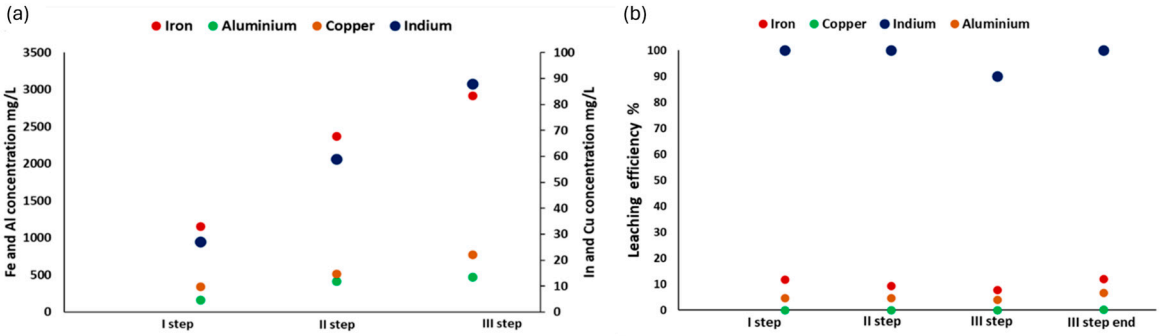


Figure 6. Metal concentrations (**a**) and extraction efficiencies (**b**) after each step during the bench scale cross-current leaching, using the finest fraction (<1 mm) (5 L leaching volume, 20% solid).

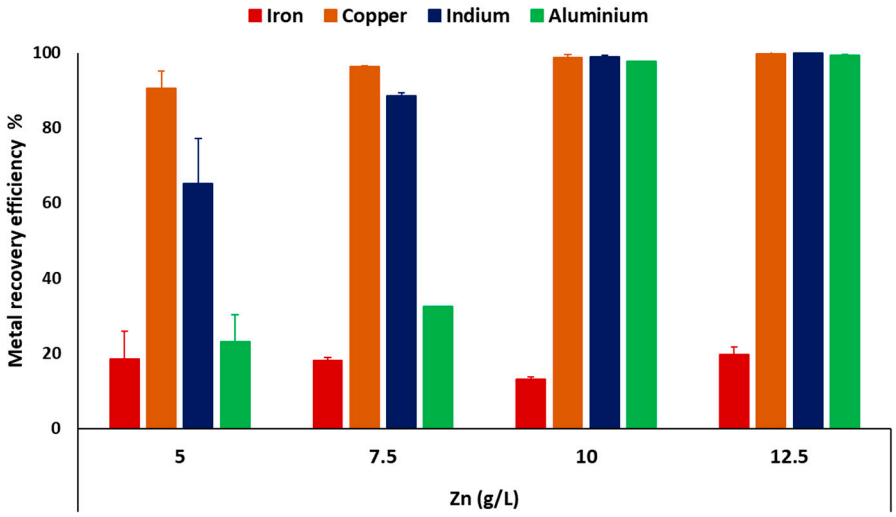


Figure 7. Metal recovery efficiencies observed in cementation treatments.

The first set of experiments confirmed the high In recovery from LCD panels, irrespective of process scale-up, and proved the feasibility of using waste from a representative SME recycler. Overall, the best operative conditions identified include the use of the finest fraction (<1 mm) only to increase In concentration in the leaching solution to 90 mg/L, performing three-step cross-current leaching with 10% solution replenishment and the use of 7.5 g/L of Zn for the cementation process, to achieve an In recovery higher than 90% while minimizing impurities (especially Al and Fe).

3.3. Assessment of Advantageous Process Configuration through the Life Cycle Methodology—Life Cycle Impact Assessment (LCIA)

3.3.1. Classification and Characterization

The results in Figure 8 aim to identify the environmental differences between the two scenarios reported in Figure 4 to assess the advantage/disadvantage of sample pre-sieving to increase In concentration. The results of classification and characterization phases show variable results according to the impact category. The possibility of an In pre-concentration in the treated waste is emphasized in the categories of resource use,

minerals and metals, and the ecotoxicity freshwater, for the avoided depletion of primary resources (Figure 8c,j). Overall, the environmental credit due to both the recovered In and the avoided disposal of LCD panels is insufficient to balance the environmental impact of the process, with the exception of Scenario 2, in the categories of climate change and eutrophication freshwater (Figure 8b,d). These positive results are mainly explained by the substantial benefit of the avoided disposal, which is able to balance the environmental burden of concrete production (the main issue of scenario 2). This burden arises from the impact of the cement required to ensure the material's technical properties. It is evident that the difference between scenarios 1 and 2 is due to the LCD amount used (3 kg with a low In concentration in scenario 1, vs. 18 kg to obtain 3 kg of high In concentration to treat in scenario 2). The lowest impact of Scenario 2 in the climate change category is also confirmed by the comparison with other innovative approaches reported in the literature, such as bioleaching followed by solvent extraction described by Falke and Höck [38]. The advantage of the SCRIPT process is explained by the short reaction time, which results in lower energy demand than the biotechnology. The different LCD amounts explain the variation between the two scenarios in the categories of ozone depletion and ionizing radiation (Figure 8g,n), where the effect of the highest energy demand for crushing is highlighted. Another interesting aspect is related to the decrease in washing water/waste LCD ratio, which affects the results of wastewater treatment (WWT). Indeed, the >1 mm fraction from sieving is sent to concrete production, without preliminary washing for sulphate removal. This reduction in wastewater represents a significant achievement from a sustainability perspective, as water treatment is one of the major weaknesses of hydrometallurgical recycling techniques [39].

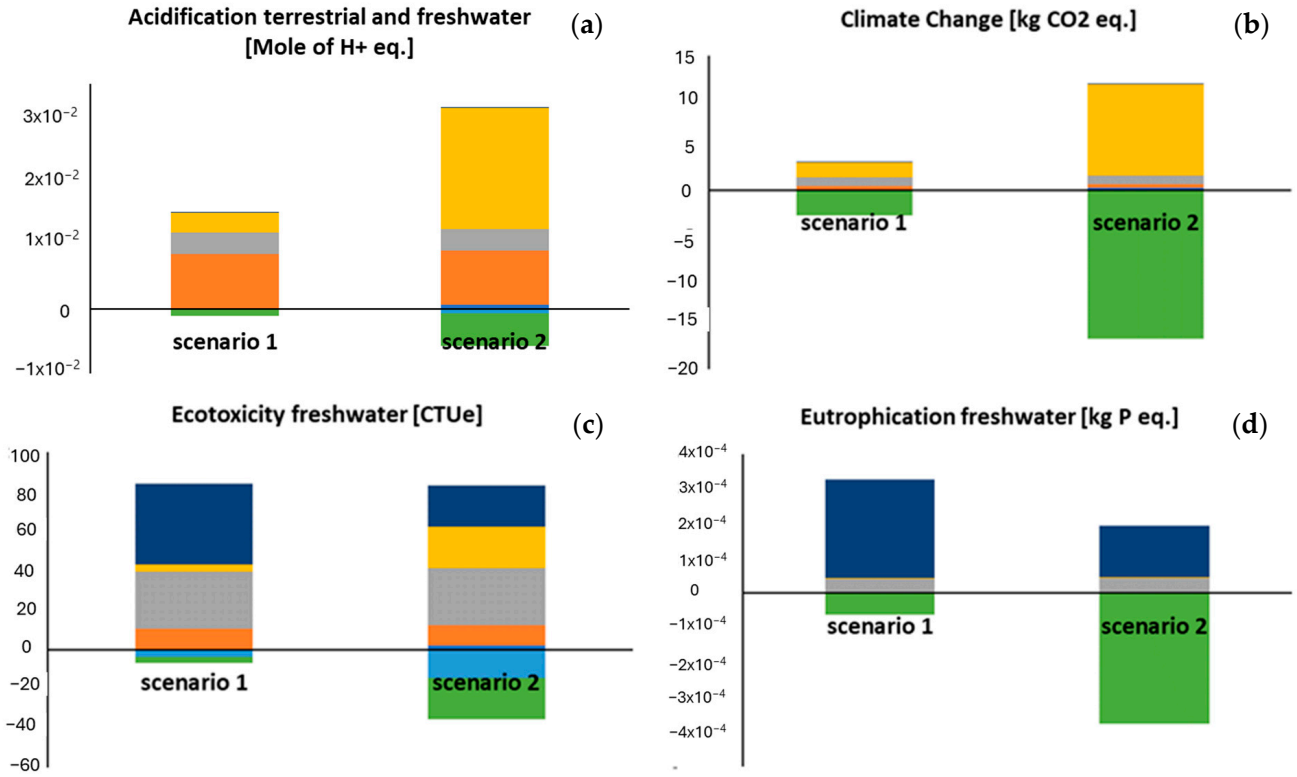


Figure 8. *Cont.*

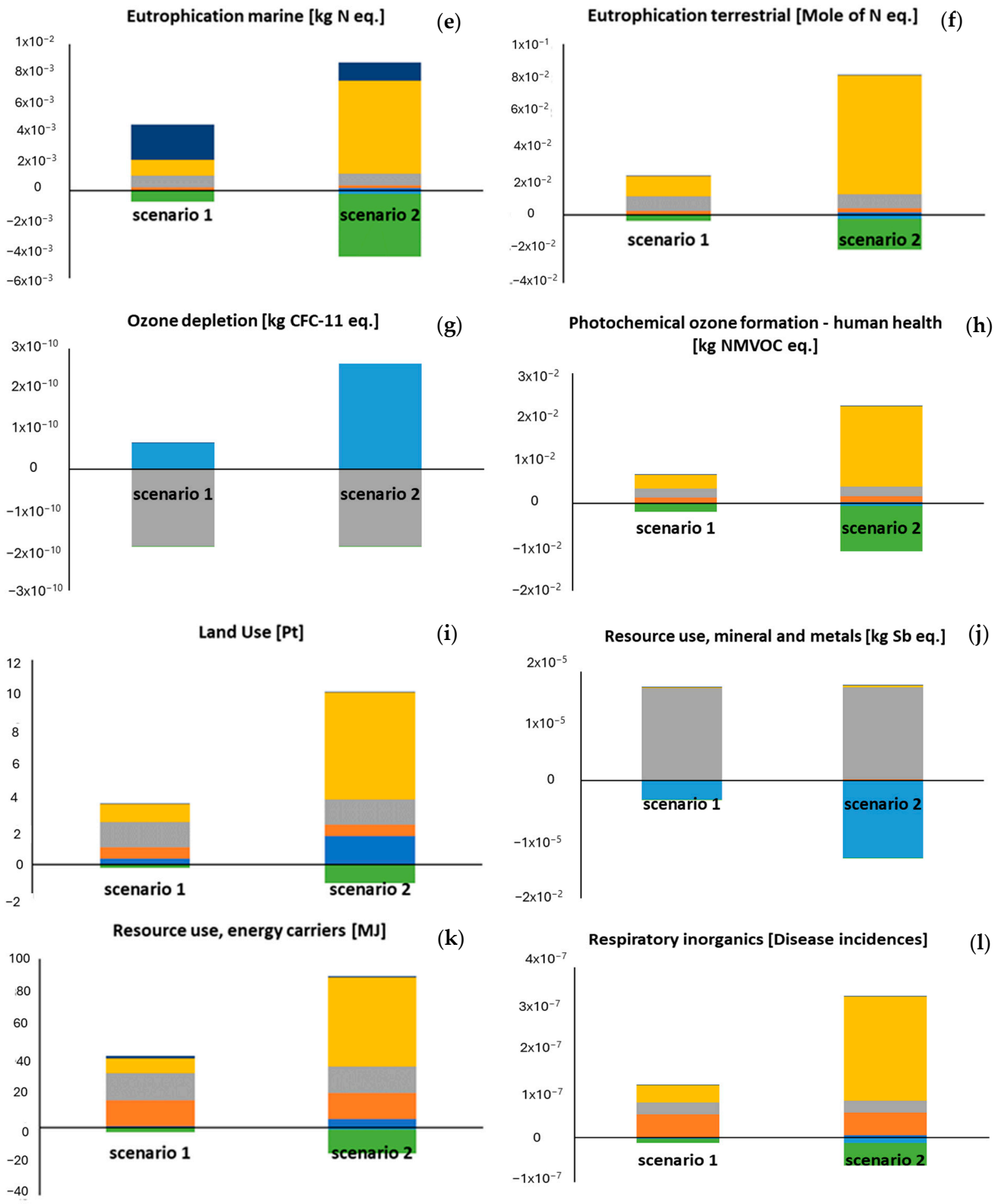


Figure 8. *Cont.*

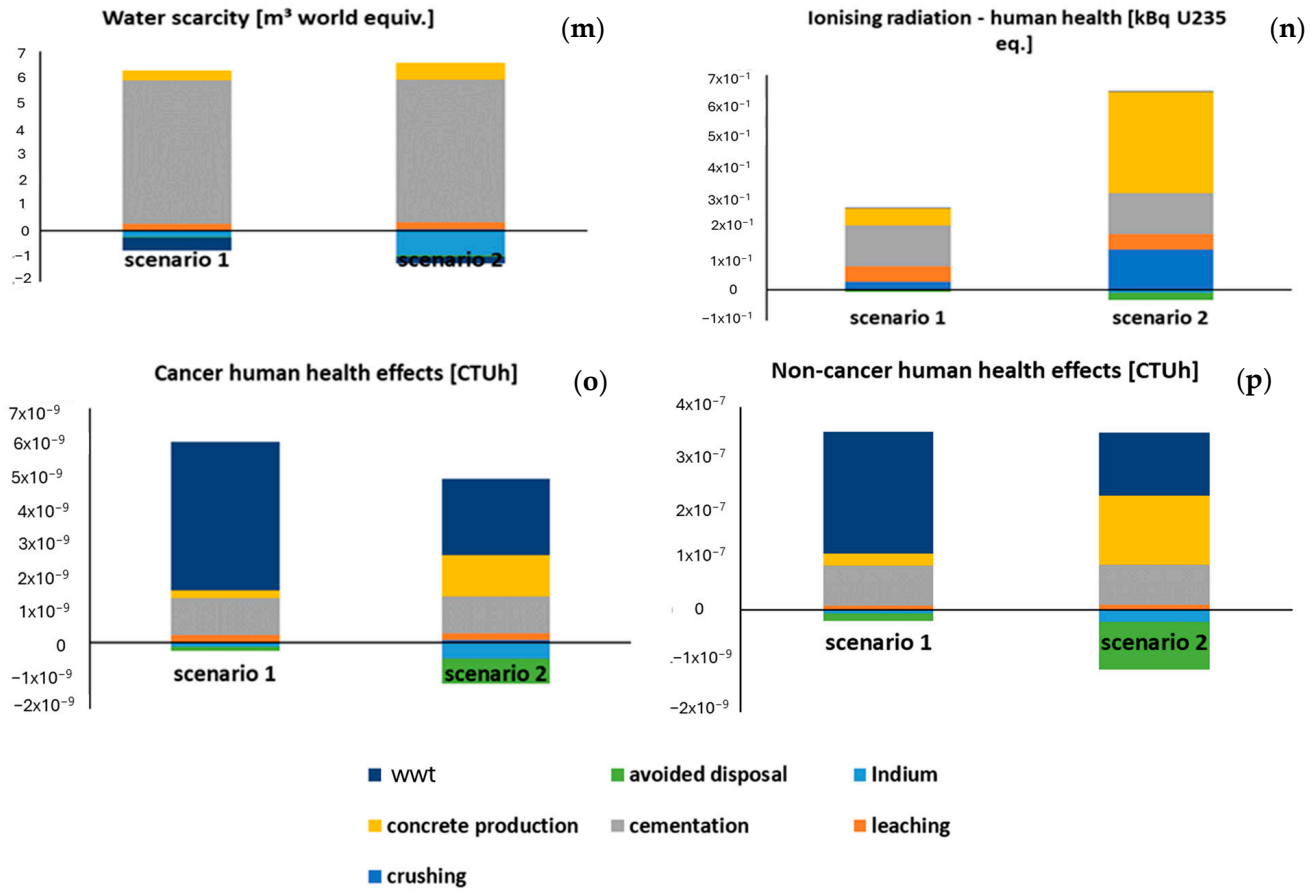


Figure 8. Results of classification and characterization steps (functional unit: a whole treatment of end-of-life LCDs in the bench scale reactor).

3.3.2. Normalization and Weighing

Considering the variability of results observed at the end of classification and characterization (described in Section 3.3.1), normalization and weighing phases were useful for providing a more complete process overview. Overall, the two options showed no relevant differences as concerns environmental aspects (Figure 9), as the higher electricity consumption for the waste pre-treatment is balanced by the benefits in both In recovery and avoided disposal. Furthermore, an additional environmental improvement of scenario 2, could be achieved at the end of optimization phase. The pie-charts in Figure 9 show relevant information about the high benefit of the environmental credit on the climate change category. On the other hand, the contribution of climate change and ionizing radiation on the impact of the whole process is due to both the NaOH used in the cementation step and the cement for concrete production. The possibility to reduce the NaOH consumption in the recovery step is discussed in Section 3.4.

The results described in Figures 8 and 9 take into account the production of a building material that fully utilizes LCD scraps generated from the In recovery process.

The sustainability assessment highlights the advantage of In pre-concentration by sieving. This benefit is mainly highlighted in the category of climate change, a very important aspect considering the current reduction targets for CO_2 emissions. The analysis proves that the In loss due to the avoided treatment of the >1 mm fraction does not affect the whole result. Overall, the main strength of the process is the possibility to fully exploit waste LCDs, avoiding their disposal. In recovery represents a highly interesting opportunity, especially considering its increasing market value, although its low concentration in waste remains a weakness in the process. Considering the described results, further optimization will be discussed in the next paragraphs, focusing on the recirculation system.

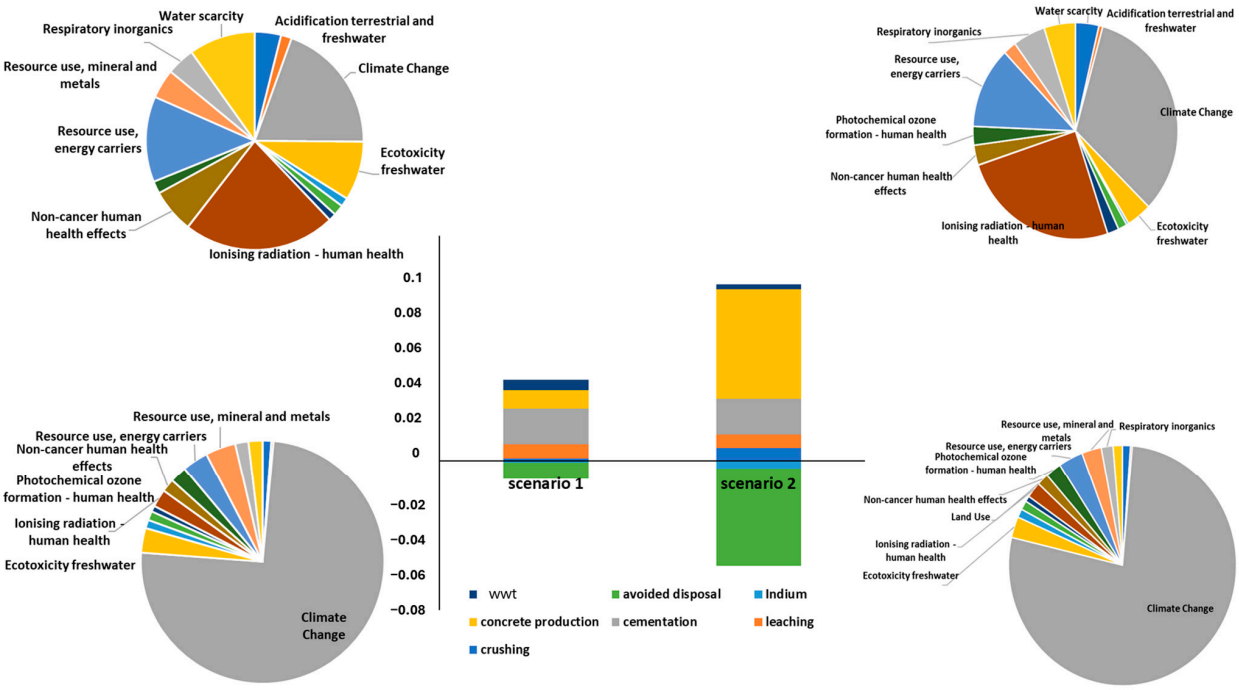


Figure 9. Results of normalization and weighing steps (functional unit: a whole treatment of end-of-life LCD in the bench scale reactor). Pie charts report the percentage of impact categories mainly affected (environmental loads) and saved (environmental credits) in each scenario.

3.4. Results of Optimization of the Patented Technology SCRIPT at Bench Scale

We investigated the possibility to recirculate: 1. wastewater from the washing step of the treated LCD, and 2. the solution resulting from the cementation step, in the bench scale facilities described above.

As shown in Figure 10, the In concentration in the leaching solution after three steps of the cross-current process was around 60 mg/L, for any cycle (Figure 10c). From these results, it is evident that the leaching efficiency was not affected by recirculation of cementation and washing wastewater. The same trend was observed for Ca, which showed the same concentration during the four cycles, around 500 mg/L (Figure 10d). On the other hand, Al and Fe concentrations grew in the fourth cycle, from around 5.5 and 0.5 g/L (in the first three cycles) to 12.0 and 1.5 g/L in the last cycle, doubling and tripling their concentrations, respectively. This increase is due to the metal intake from the washing solution, mainly for Al. The Fe and Al concentrations, in the resulting washing solution, were around 1.5 and 1.0 g/L in the fourth washing step, respectively (Figure 11a,b). On the other hand, In and Ca concentrations in the washing solution were constant around 5–10 mg/L and 500 mg/L, respectively (Figure 11c,d).

As concerns the further recovery steps, the results showed for the amount of NaOH necessary to increase the pH to the value of 2.5 decreased from 150 g/L, in the first step, to around 70–80 g/L in the second, third, and fourth cycles (Figure 12b). Furthermore, the amount of In that precipitated during the pH adjustment in the first three cycles was negligible (Figure 12a). On the other hand, in the fourth cycle, In recovery was around 40%, comparable to Al and Fe precipitation efficiencies.

The cementation process, with 7.5 g/L of Zn, achieved an In recovery efficiency higher than 90% across all the recirculation cycles tested; the same was obtained without recirculation (Figure 13a). In contrast, Al and Fe recovery efficiencies decreased from 95 to 40%, in the first three cycles, to 20 and 0% in the last cycle, respectively, increasing the In purity in the final product. This was probably due to a lower pH increase in the fourth cycle, reaching a value lower than four, instead of a value higher than six, in the first two cycles (Figure 13b).

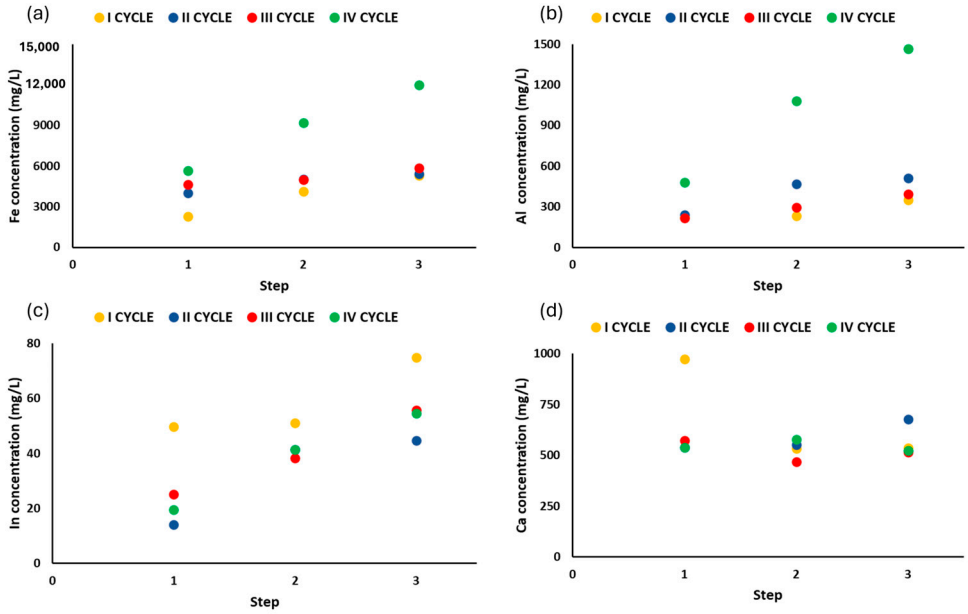


Figure 10. Metal concentrations ((**a**) Fe, (**b**) Al, (**c**) In, and (**d**) Ca) during the 3-step cross-current leaching process for the four tested recirculation cycles.

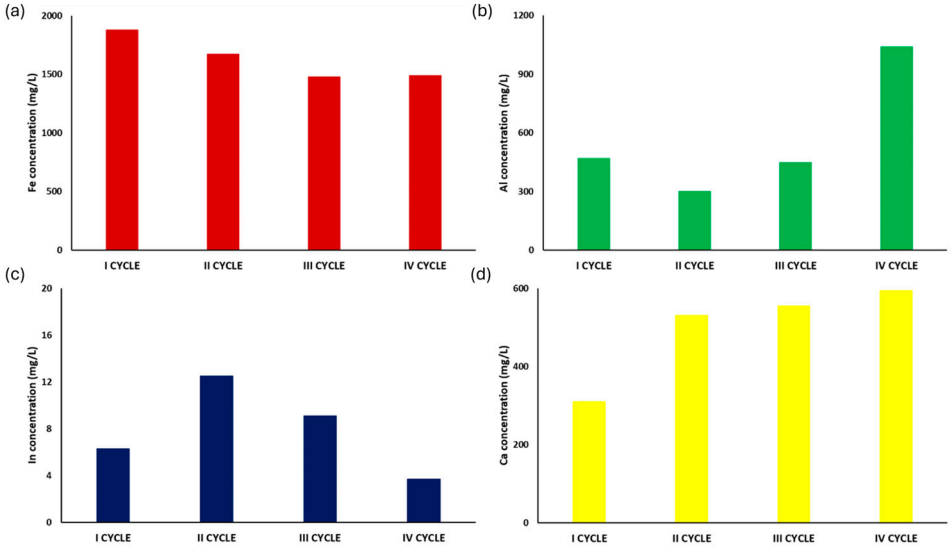


Figure 11. Metal concentrations ((**a**) Fe, (**b**) Al, (**c**) In, and (**d**) Ca) in the solution after treated LCD washing.

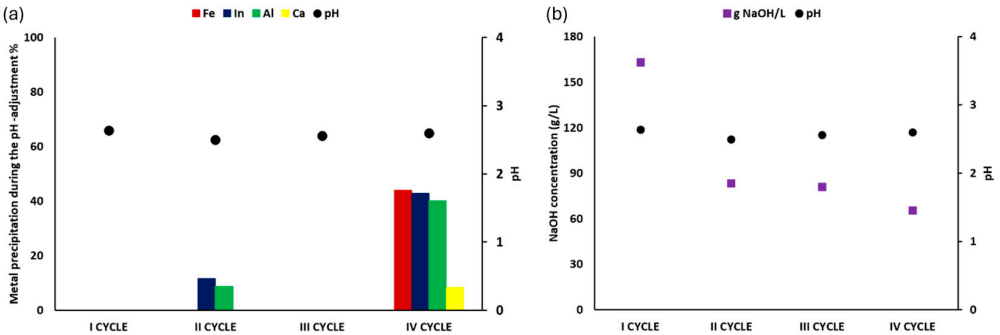


Figure 12. Metal recovery efficiencies (**a**) and NaOH concentration in the pH adjustment step (**b**).

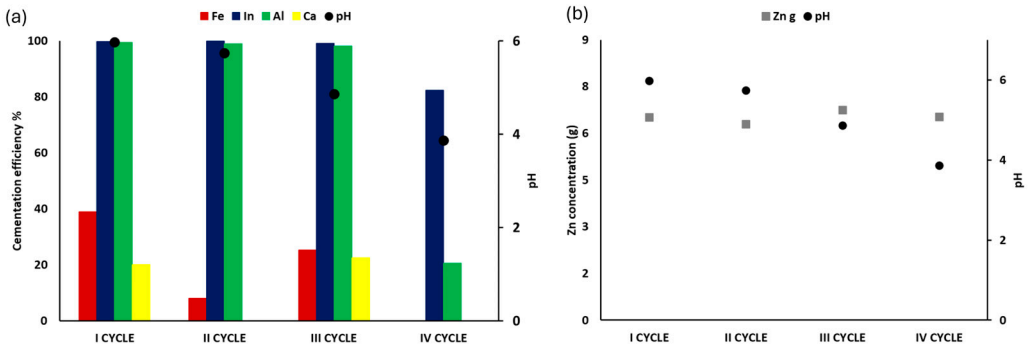


Figure 13. Cementation efficiencies (**a**) and amount of Zn (**b**) used in cementation for In recovery.

These findings confirmed the possibility of recirculating cementation and washing wastewater flows, without reducing the leaching efficiency. The recirculation system allowed for reductions in both the water demand and the volume of wastewater flows to manage. Furthermore, the NaOH demand, for the pH adjustment before the cementation step, was halved due to the recirculation system.

Therefore, the advantage of reduced impurities in the final solid product is further enhanced by a relevant environmental benefit. In this regard, in a previous work, Amato et al. [40] estimated a decrease of 25% in process emissions by the effective wastewater recirculation system.

3.5. Economic Sustainability

The estimation of process costs represents essential information from the perspective of process scale-up. Considering the process peculiarities, its cost-effectiveness is strongly influenced by the market volatility of both metals and raw materials. In addition to economic aspects, the social and sociological issues of electronic waste recovery can be analyzed to cover all the sustainability spheres [38]. Indeed, the creation of an effective recycling system, supported by the legislation for environmental and communities protection, should allow for the social impacts of the mining activities to be avoided [39]. Furthermore, the positive social impact includes increased job opportunities, poverty reduction, and the promotion of economic development [38,41,42].

The economic sustainability analysis refers to a 1 m^3 reactor, able to treat 800 kg of panels per day (four step process), for 210 treatments per year. In addition to In, we also considered the excess of Zn from the resulting product as valuable metal. The investment costs are not considered in the economic assessment: the relatively low concentration of In does not justify any investment being dedicated only to In recovery, and the idea is to use the same plant to recover different valuable metals from other residues. The simple design of the plant (a mill, a jacketed reactor, a stirred reactor, a filter press, capex around EUR 120,000) makes it suitable for the implementation of additional treatments; therefore, we considered the facility cost depreciated.

The economic assessment includes several variables, such as the energy and raw material costs and the fluctuations of the metal market. As concerns the operative costs, they were estimated around 350 EUR/cycle with four leaching steps, translated into 73,000 EUR/year, considering 210 cycles for year. The H_2SO_4 demand causes the highest contribution (34% of the OPEX), followed by NaOH and Zn (26% and 23%, respectively) (Figure 14). This cost distribution confirms the importance of wastewater recirculation, which increases the pH of the solution and decreases the NaOH demand. The additional recovery of Zn from the excess in the solid product could further reduce operating costs.

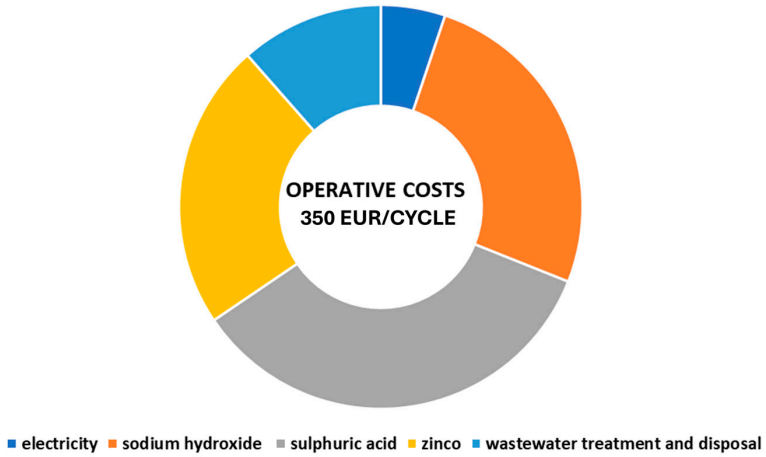


Figure 14. Distribution of operative costs for the process (1 m^3 reactor, four steps of cross-current leaching).

As previously observed, the cost-effectiveness of the process is connected to the In concentration in the starting waste. The trend in the ideal concentration, which makes the process sustainable, is closely linked to market fluctuations. For example, in recent years, the indium price fluctuated from 280 EUR/kg (requiring a concentration of 1200 ppm) to 400 EUR/kg in July 2024. Under these economic conditions, also described in paragraph 2.5, 600 ppm is the concentration able to produce a profit, making the innovative process sustainable from an economic point of view also (Figure 15). The recovery of other metals, such as Cu and Al, is not economically viable. Given the current price of around 9 EUR/kg for Cu and 2 EUR/kg for Al [43,44], the additional cost of integrating a process for Cu and Al recovery is not sustainable compared to In, which has a price 40 times higher. Considering the importance of the identification of sustainable strategies for In recovery, additional efforts should be made in pre-treatment to obtain a higher In pre-concentration (along with mixing different waste with relevant metal content). In the study by Savvilotidou et al. (2019) [45], several pre-treatment methods (mechanical crushing and sieving, pyrolysis, a gravimetric method, thermal shock) were compared based on In concentrations and potential economic savings. The findings indicated that thermal shock is the most effective pre-treatment technique, achieving a maximum In pre-concentration yield of 77.4% [46–49]. However, the economic analysis confirmed that mechanical crushing and sieving is the most cost-effective option, followed by thermal shock and pyrolysis. These results suggest that further incorporating a pre-sorting step (e.g., thermal shock to separate polarizers) could be a promising solution to increase the starting In concentration in the LCD waste.

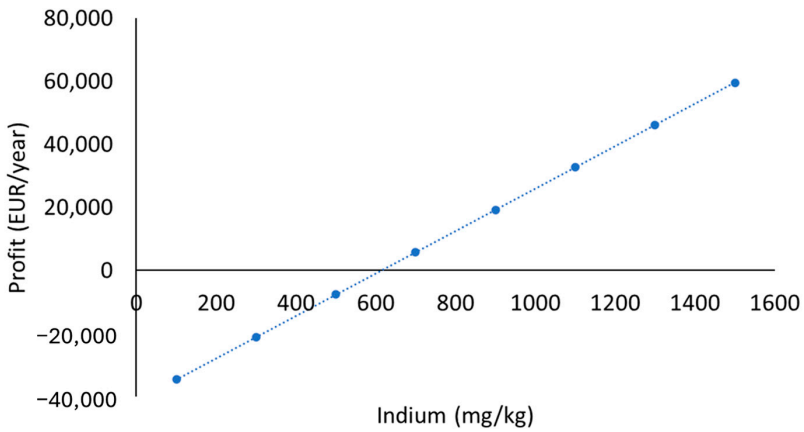


Figure 15. Process profit (EUR/year) vs. indium concentration in the feed material (plant capacity 160 t/y).

The present evaluation confirms the necessity of combining the developed process with additional recycling treatments to reduce investment costs. Overall, our study is fundamental not only for boosting indium recycling in the world, but also to present a methodological approach to meet sustainability goals within circular economy approaches for strategic metals in complex matrices.

3.6. Obstacles to Scaling Up

Given the simple design proposed by the patent, we do not see significant obstacles to the process scale-up, apart from the typical market fluctuations for raw materials and products, which could affect the process sustainability. Nevertheless, these are common issues in any recycling process.

Another challenge could be linked to a variation in In concentration, in the event it will decrease in LCD devices.

In recent years, WEEE has become a pressing global issue, increasing at an annual rate of 3–4% due to economic growth and the expanding use of electronics in everyday life. By 2030, their amount is expected to exceed 74 million tons [50]. Although the weight of WEEE is not a definitive indicator, since its composition changes over time, an estimate of future WEEE composition can be made based on the types of products currently being introduced to the market [51], and LCDs represent a substantial portion of electronic waste [52]. Currently, as already reported, LCDs are widely used in televisions, laptops, desktops, and other devices, and contain 0.12–0.14% liquid crystals whose main ingredient is indium-tin oxide. Consequently, approximately 90% of the indium produced annually is used for LCD manufacturing [51], ensuring the availability of waste quantities to support the recycling industry.

Another issue in scaling up the process relates to the fluctuating cost of Zn used in the cementation process. Currently, this is not a major limitation, as Zn costs have decreased to a quarter of those reported in Table 1. Furthermore, an alternative solution could be the replacement of Zn powder cementation with an electrodeposition process, to reduce Zn consumption. The effectiveness of electrodeposition was already demonstrated in studies by Song et al., where a two-step electrodeposition process allowed the achievement of a 99.41% recovery rate for In [53,54].

4. Conclusions

Indium concentration in LCDs is higher than that in ores, making LCD scraps an attractive opportunity, given its growing market value. The SCRIPT patent offers a solution for In recovery from end-of-life LCDs, able to combine high technical performance, sustainability, and a simple design thought process considering industrial scale implementation. In this regard, the present paper shows how the integration of experimental activity and sustainability analysis (both environmental and economic) drives the validation and optimization of this innovative process. Overall, the results show In recovery efficiency over 90%, with excellent selectivity over the main interfering elements.

The general process scheme includes preliminary pre-treatment of crushing and sieving with the finest fraction (<1 mm), cross-current leaching in three steps with 10% refreshing of the leaching solution, and recovery by cementation with 7.5 g/L of Zn. An additional unit for wastewater recovery and recirculation was included to reduce water and raw material consumptions.

This study enhances environmental benefits due to the avoided disposal of the displays, and highlights the economic relevance of In concentration in treated waste, identifying >600 ppm as the threshold for process sustainability. Considering the simple design of the process, metal market fluctuations are identified as the main limitation in process scale-up; however, this is a common issue in all recycling processes. Additional advantages for society can be hypothesized thanks to the creation of new job positions and a regulated recycling system of waste LCDs, as an alternative to their illegal exportation towards poorer countries. The integration of all sustainability spheres (environmental, economic,

and social) during the optimization of the recycling process represents an excellent example of circular economy implementation.

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Analysis of the Environmental and Economic Effect of the Co-Processing of Waste in the Cement Industry in Korea

Dowan Kim * and Chaegun Phae

Department of Environmental Engineering, Seoul National University of Science and Technology, Seoul 01811, Republic of Korea

* Correspondence: dowan2050@nate.com; Tel.: +82-10-6218-6617

Abstract: Recently, the amount of waste generated in Korea has been increasing, and there have been difficulties disposing of it. As an energy-intensive and raw-materials-oriented industry, the cement industry is facing challenges including overcoming the climate crisis and achieving carbon neutrality. Co-processing was suggested as a solution, but the environmental effects of this have not been specifically studied in Korea. In this study, the effects of using alternative resources (limestone, silica stone, iron ore, and gypsum) and fuel on greenhouse gas (GHG) emissions in the cement industry in Korea were analyzed. GHGs generated from mineral mining were compared to GHGs of alternative resources. The reduction in GHGs by using alternative fuel was calculated via the amount of heat from waste instead of that from bituminous coal. Co-processing can reduce approximately 106.9 kg of CO_2 in one ton of cement. The cost savings were estimated to be about USD 3815 million. In addition, the lifespans of landfills would be extended by 7.55 years.

Keywords: cement; co-processing; waste; greenhouse gas; alternative effect

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1. Introduction

With industries growing rapidly and various improvements in people's quality of life, the total amount of waste generated in Korea is also increasing [1]. However, it is difficult to increase the capacity of waste treatment facilities [2,3].

According to Korea Energy Agency, the energy consumption of the domestic cement industry in 2019 was 4.4 million toe, an increase of 4.4% compared to the level in 2018, and the more than 50% of the energy consumption was from coal (bituminous coal).

A treatment called "co-processing" (the use of waste as an alternative raw material) in the cement industry can replace natural materials or energy sources [4,5]. Additionally, this method has been proven to be a sustainable waste management method in that it does not generate secondary waste, reduces GHGs, and is operated stably at high temperatures [6–9]. The EU cement industry already substitutes 43% of its fossil fuels with alternative fuels derived from waste and biomass to supply thermal energy in clinker-making processes.

However, in Korea, there have been no studies on the contribution of co-processing to the cement industry. For this reason, more focus is being placed on emissions from dioxins, carbon monoxide, and heavy metals, which can be easily measured, rather than the positive effects of co-processing. As a result, the government is having difficulties making policy decisions about the expansion of co-processing.

Wastes can be used as fuel and as raw materials in the cement industry. Most are inorganic substances that can be sent to landfills, with fly ash accounting for 39.3% and inorganic sludge accounting for 19.6%. In addition, waste synthetic resin accounts for the largest amount of fuel, 12.6% (Table 1).

Coal ash and inorganic sludge contain chemical components (e.g., SiO_2, Al_2O_3) that are necessary for the manufacturing of cement; using coal ash as a raw material for cement is encouraged in situations in which landfilling is more difficult. Many countries manufacture cement from coal ash, enabling sustainable cement production [10].

Table 1. The amounts of wastes in co-processing in the cement industry in Korea (2019).

Category			Ton/Year	%
Resource	Fly ash	Domestic	2,227,312	39.3
		Import	951,729	
	Sludge	Organic	727,435	9.0
		Inorganic	1,587,714	19.6
	Slag		245,742	3.0
	Dust		25,515	0.3
	Catalyst		13,420	0.2
	Gypsum and lime		108,608	1.3
	Ash		16,232	0.2
	Adsorbent		9076	0.1
	Soil		148,167	1.8
	Metal		-	-
	Foundry and sandblast		606,047	7.5
	Glass		23,764	0.3
	Ceramics		-	-
Fuel	Tire	Domestic	170,905	2.1
		Import	103,787	1.3
	Synthetic resin		1,015,799	12.6
	Rubber		75,931	0.9
	Wood		35,449	0.4
	Other		5	0.0
Total			8,092,643	100.0

A large amount of energy is required for cement curing. Municipal solid waste is a viable choice to replace a portion of fossil fuel use [11]. Therefore, the energy requirement can be economically met by waste synthetic resin.

Korea's cement production is 50,635,456 tons (19). The amount of waste used as an alternative resource and fuel in the cement industry amounted to 8,092,643 tons in 2019. Considering that the annual amount of waste is about 181,491,870 tons/year, the corresponding amounts recycled in the cement industry are 4.5% and 5.2% of the total amount of waste recycling. This is similar to other treatment methods, such as incineration or landfills, considering that 5.2% of waste is incinerated and landfills account for 6.1% of the nation's waste.

In this study, the effects of co-processing in the cement industry in Korea were analyzed in terms of the levels of reduction in raw materials and fuels, coal mining, GHG emissions, factor emissions, and installation costs for incineration and landfill facilities. This study is unique in that it identifies the effect of substituting natural resources and reducing the GHG emissions factor in coal mining based on the status of the cement industry in Korea.

2. Method

2.1. Analysis of Alternative Effects of Resources

The status of co-processing was determined using statistical data from the Korea Cement Association (KCA). Alternative effects were analyzed in terms of environmental aspects. Regarding the environmental aspects, the reduced use of natural resources and the contribution towards carbon neutrality via the reduction in GHG emissions were evaluated.

To calculate the effect of co-processing in the cement industry, it is necessary to examine the amounts that can be saved by recycling. To this end, the effects of alternative natural minerals and fossil fuels were analyzed. The amounts that can be reduced by recycling natural resources, such as limestone, clay, and siliceous raw materials, which are currently used in the process of manufacturing cement, were calculated [12].

In terms of economics, the reduced social costs of disposal due to the recycling of waste and the reduced import costs of bituminous coal were evaluated. Wastes can be used as fuel and as raw materials in the cement industry.

Firstly, the amounts of natural resources that can be reduced by recycling, such as limestone, clay, and siliceous raw materials, were calculated. This was based on the amount of limestone used and the ratio of raw materials required for cement production.

The GHG emissions factor was applied as clay (276.7 kg CO_2/t-prod), silica (12.3 kg CO_2/t-prod) [13,14], iron ore (35.4 kg CO_2/t-prod), and gypsum (100 kg CO_2/t-prod) [15,16]. The exchange rate is 1289.81 USD per 1 KRW. The calculation formulae are expressed here as Equations (1)–(3).

$$\begin{aligned} &GHG\ reduction \\ &= \sum_{i=1}^{n} (\text{alternative of Resource } x_i) \times (\text{emission GHG mining resource } x_i) \end{aligned} \quad (1)$$

The net calorific value of bituminous coal for fuel is 5660 kcal/kg, while it is 8170 kcal/kg for petroleum coke [17]. Calorific values (kcal/kg) were applied to data (average of 6 large cement companies) provided by the KCA. Bituminous coal consumption and the reduction effect of GHGs were calculated using Equations (3) and (4). The emission factor of bituminous coal was calculated by applying IPCC 06.

$$\begin{aligned} &Coal\ consumption\ reduction \\ &= \text{alternative fuel calorific value(kcal)} \div \text{ Coal calorific value (kcal/kg)} \end{aligned} \quad (2)$$

$$\begin{aligned} &Reduction\ effect\ of\ GHG \\ &= \text{Coal consumption reduction}\left(\frac{\text{tons}}{\text{year}}\right) \times \frac{2.44\text{t } CO_2}{\text{Bituminous coal}-\text{t}} \end{aligned} \quad (3)$$

2.2. Savings Associated with Waste Treatment Facility Installation and Operation Costs

Co-processing not only reduces the installation cost of the waste treatment facility (WTF), but it also reduces the costs of operating the WTF. The costs can differ depending on the operation method, but these factors must be considered as major contributions of co-processing. The operating cost was calculated by referring to the estimated regression equation derived in previous work [18]. The dummy variable index was excluded from the review process because it is difficult to calculate this separately, as it is related to incidental costs and profits and includes such processes as incineration heat recovery, power generation, and leachate treatment. The estimation formulae used to calculate the operating cost are expressed as Equations (4) and (5).

The Ministry of the Environment (MOE) has set a standard installation cost unit. For the incineration facility, the operation rate was set to 85% (310 days out of 365 days). The cost per unit for installation applied here was KRW 381 million/ton, and the lifetime of the incineration facility was 20 years.

$$\begin{aligned} &\text{The operating cost of incineration} \\ &= \ln(Co) = 3.349 + 0.656\ln(Q) + 0.416\ln(Cu) - 0.181D \end{aligned} \quad (4)$$

Co: Operating cost (million KRW),
Q: Facility capacity (ton/day),
Cu: Operation rate (1% = 1),
D: Dummy variable

$$\begin{aligned} &\text{The operating cost of the landfill site} \\ &= \ln(Co) = -0.238 + 0.3056\ln(Al) + 0.321\ln(A) + 0.384D \end{aligned} \quad (5)$$

Co = e(ln (Co))
Co: operating cost (million KRW),
Al: annual landfill (m^3/year),
A: landfill area (m^2)
D: Dummy variable

2.3. Effect of Extending the Life of the Landfill

It is not recommended to extend the lifespan of landfills currently in operation as much as possible due to the limited lifetimes of existing landfill sites and the difficulties installing new landfill sites. The cement industry can expand the lifespan of landfill facilities by treating large amounts of waste.

An estimation of the effect of expanding the life of landfills was conducted by calculating the remaining landfill capacity and annual landfill volume of current landfills. To estimate the lifespan extension of landfills, the remaining landfill capacities and annual landfill volumes of current landfills were calculated and investigated. The life extension effect of co-processing was also calculated using Equation (6), assuming that the load on each landfill site was reduced by the capacity calculated when applying the density and ash amount for each type of waste created in the cement industry.

$$\begin{aligned} &Extending\ life\ of\ landfill \\ &= \frac{\text{Residual capacity of industrial waste landfill facility}}{① + ②} \end{aligned} \tag{6}$$

① *the Amount of Annual industrial waste landfill*
② *the Amount of waste that must be brought to landfill, if it is not treated by co − processing*

3. Results

3.1. GHG Reduction Effects of Alternative Resources

Table 2 shows the amount of GHG emissions, the amount of alternative resources due to waste recycling in the cement industry, and the amount of GHG emissions generated in the process of mining resources. Additionally, it was found that annual emissions were reduced by 304,945 tons of CO_2 per year, with 130 kg saved per ton of cement and a reduction in GHGs of 31.1 kg CO_2. This amount is only 4~6% of the GHG emission factor, which is currently 510 to 712 kg CO_2/ton of cement of the entire cement industry [19]. However, it can be seen that there is a carbon-neutral effect, even reducing raw materials. In addition, since Korea has mined all of its limestone, it is omitted from this calculation. If lime can be obtained from waste, more greenhouse gases can potentially be reduced.

Table 2. Alternative resource effect via co-processing.

Category	Alternative (Ton/Year)	Emission of GHG during Mining ($kgCO_2$/Ton)	GHG Reduction ($kgCO_2$/Year)
Limestone	-	-	-
Clay	5,706,601	276.7	1,579,016,497
Silica	629,811	12.3	7,746,675
Iron	245,742	35.4	8,699,267
Gypsum	108,608	100.0	10,860,800
Total	6,690,762	-	1,606,323,239
GHG reduction effect by one ton of cement ($kgCO_2$/ton cement)	-	-	31.7

3.2. GHG Reduction Effects of Alternative Fuel

The use of alternative fuels in the cement industry amounts to 1,998,379 tons/year, which has the effect of replacing approximately 24% of the total calories (Table 3). We can compare this figure to that of Germany, which replaces 68.9% of its energy with waste [11], a level that amounts to a third of its total. Co-processing can save about 62.3 million USD/year based on the import price of bituminous coal. The amount of calories used is divided by the amount of bituminous coal, and the reduction in GHGs is 75.2 kg CO_2. The reduction effect in the GHG emissions is lower than that of 89 kg CO_2-equivalents per ton of cement [20]. However, the use of alternative fuels is limited because they usually contain

impurities, such as chlorides, which, when present in sufficiently high concentrations, can affect the quality of Portland cement clinkers [21].

Table 3. Alternative fuel effect via co-processing.

Category		Consume (ton/year)	Calories (kcal/kg)	Total Calories (Gcal)
Fuel	Bituminous coal	3,702,000	5660	20,953,320
	Petroleum coke	858,000	8170	7,009,860
	Total (A)	4,560,000	-	27,963,180
Alternative Fuel	Textile	3.5	3000	11
	Tire	274,692	6073	1,668,070
	Synthetic resin	1,015,799	4500	4,571,097
	Rubber	75,931	4730	359,155
	Wood	35,449	3500	124,072
	Waste Derived Fuels	587,821	3500	2,057,372
	Solid Refuse Fuel	8683	6000	52,098
	Total (B)	1,998,379	-	8,831,874
Alternative calorie ratio (B/(A + B)) × 100				24%
Bituminous Coal Alternative Calorie (B ÷ 5660 kcal/kg × Gcal/10^6 kcal × 1000 kg/ton)				1,560,402 ton
GHG reduction effect by one ton of cement ($kgCO_2$/ton cement)				75.2

3.3. Waste Treatment Facility Installation and Operation Cost Savings

The effect of reducing the installation costs of landfills and incineration facilities by recycling waste was analyzed and is presented in Table 4. These values were calculated by considering recycling combustible waste in the cement industry. It was found that 1767.2 million USD can be saved in terms of the installation costs of incineration facilities to treat waste that is subject to incineration. The corresponding figure is 1.7 USD for the incineration facility installation costs per ton of cement.

Table 4. Incineration facility installation cost and savings by co-processing.

Category		Value	Note
Incineration target waste (ton/year)	Organic sludge	727,435	
	Textile	4	
	Synthetic resin	1,015,799	
	Rubber	75,931	
	Wood	35,449	
	Total	1,854,619	(A)
Required capacity for incineration (ton/day)		5983	(B) = (A) ÷ Operating day (310 day)
Installation costs (million USD/year)		1767.2	(C) = (B) × 3.81 (100 million KRW/ton) × Exchange Rate
Incineration facility depreciation (million USD/year)		88.4	(D) = (C) ÷ 20 year
Savings of cement per ton (USD/year/ton)		1.7	(E) = (D)/Production of cement

Non-combustible and incineration ash generated after the incineration of combustible waste becomes a target material, and approximately 2046.8 million USD is saved out of the total installation cost of constructing a landfill for disposal, which is equivalent to 1.4 USD/ton of cement (Table 5). The operating cost of a landfill was calculated and found to be 42.1 million USD/year, and an operating cost of 8.4 million USD/year was found to be necessary.

Table 5. Landfill installation cost and savings via co-processing.

Category		Landfill Volume (m^3)	Note
Direct landfill waste (non-combustible waste)	Fly ash	1,484,875	Mixed waste for landfill
	Inorganic sludge	1,044,549	Industrial wastewater treatment sludge
	Ash	10,821	Mixed waste for landfill
	Adsorbent	11,345	Ion exchange resin
	Soil	92,604	Construction waste
	Foundry and sandblast	336,693	Foundry
	Glass	19,803	Glass
	Total (A)	3,000,690	
Post-Incineration landfill waste	Organic sludge	43,646	Mixed waste for landfill
	Textile	0	
	Synthetic resin	39,278	
	Rubber	1853	
	Wood	1394	
	Total (B)	86,171	
Total (C)		3,086,861	(A) + (B)
Installation cost (million USD/year)		2051.3	(C) × 22.2 USD/m^3 × 30 year
Landfill depreciation (million USD/year)		68.4	(D) ÷ 30 year
Savings of cement per ton (USD/year/ton)		1.4	(E) = (D)/Production of cement

According to the Japan Cement Association, the use of waste in the cement industry can extend the lifetimes of existing landfills by 5.3 years [22]. The amount of waste estimated to be disposed of in landfills is 3,644,089 m^3/day, which is equivalent to 89% of the annual landfill amount of 3,086,861 m^3/day [23]. As a result of this review, it was found that the lifespan of an industrial waste landfill facility that can be extended by treating waste in the cement industry is 7.55 years (Table 6). Therefore, the effect of extending the lifespan of landfills via co-processing is clear. If co-processing is not implemented, there is a high possibility this will create social problems due to the rapid increases in landfill volumes.

Table 6. Extending the lifespan of landfills for industrial waste via co-processing.

Category	Value	Note
Industrial waste reclamation facility (except public) Remaining landfill capacity (A)	59,969,819	m^3
Annual Industrial waste landfill (B)	3,644,089	m^3
Landfill life (C)	16.46	year, B/A
Amount of landfill if not brought in from the cement industry (D)	3,086,861	m^3
The remaining lifetime of landfill facility when the cement industry does not co-process waste (E)	8.91	year, A/(B + D)
Effect of extending (year)	7.55	C-E

4. Conclusions

Co-processing in the cement industry enables the calculation of benefits in the form of costs, specifically in terms of reductions in the installation and operation costs of waste treatment facilities as well as reductions in GHGs. Large amounts of remnants (waste and by-products) which are inevitably generated from national infrastructure facilities, such as those of the power generation industry and the steel industry, as well as those in social infrastructures, such as sewage treatment facilities and incinerators, can be stably and effectively recycled.

As the cement industry uses waste as an alternative resource and fuel, the alternative effect of each 31.7 kg CO_2/ton cement and 75.2 kg CO_2/ton cement, total GHG reduction per ton of cement is 106.9 kg CO_2.

The GHG reduction effect in the cement industry has been frequently analyzed, but the raw materials/fuel supply and demand conditions in Korea have not. This study analyzed the GHG reduction effect based on the current status of Korea's cement industry, which can be regarded as a substantial. In particular, while GHG reductions have only been calculated for the effects of fuel substitution, this study derived the effects of raw material substitution.

The cement industry of Korea is facing challenges including overcoming the climate crisis and achieving carbon neutrality, as an energy-intensive and raw-material-oriented industry. Co-processing in the cement industry reduces GHGs.

The cost savings were estimated to be about 3815 million USD. In addition, the strategy discussed here would extend the expiration dates of landfills at domestic industrial waste reclamation facilities by 7.55 years.

The cement industry can play an important role in recycling the waste that is inevitably generated, incinerated, and put into landfills. Kilns have many advantages compared to incineration, and it is possible for them to contribute to zero landfill use while also serving to economically and stably stabilize treatment costs via recycling. One problem is that it is necessary to increase the acceptance of residents by operating these facilities in an eco-friendly manner while minimizing secondary pollution in the process of bringing waste into the facility, running pre-treatment programs at the facility, and operating the heat treatment of kilns. To this end, it is necessary to closely manage imported waste to minimize the import of hazardous substances as well as to invest continuously in sealing facilities and upgrades to air pollution prevention facilities.

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Review

Advancements in PET Packaging: Driving Sustainable Solutions for Today's Consumer Demands

Beenu Raj [1], Jitin Rahul [2,*], Pramod K. Singh [2], Velidandi V. L. Kanta Rao [3], Jagdish Kumar [4], Neetu Dwivedi [5], Pravita Kumar [6], Diksha Singh [7] and Karol Strzałkowski [7,*]

1 Department of Environment Science, PGDAV College NCWEB Centre, University of Delhi, New Delhi 110007, India; raj.beenu8@gmail.com
2 Department of Environmental Sciences, Sharda School of Basic Sciences & Research, Sharda University, Greater Noida 201310, India; pramodkumar.singh@sharda.ac.in
3 CSIR-Central Road Research Institute, Bridge Engineering and Structures Division, New Delhi 110025, India; vvlkrao.crri@nic.in
4 CSIR-Central Institute of Mining and Fuel Research, Dhanbad 826001, India; jagdish.cmri@gmail.com
5 Department of Environmental Science, Sri Aurobindo College, University of Delhi, New Delhi 110062, India; dwivedi.neetu@gmail.com
6 Department of Chemistry, Sri Aurobindo College, University of Delhi, New Delhi 110062, India; pravita.kumar@gmail.com
7 Institute of Physics, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University, Grudziadzka 5, 87-100 Torun, Poland; diksha@doktorant.umk.pl
* Correspondence: jitin.rahul@sharda.ac.in (J.R.); skaroll@fizyka.umk.pl (K.S.)

Abstract: This work provides an overview of the importance of recycling PET waste to reduce the environmental impact of plastic waste, conserve natural resources and energy, and create jobs in the recycling industry. Many countries have implemented regulations and initiatives to promote the recycling of PET waste and reduce plastic pollution, such as extended producer responsibility (EPR) systems, bans on certain single-use plastics, and deposit–return systems for plastic bottles. The article further underscores the versatility of recycled PET, as it can be transformed into various products such as fibers, sheets, film, and strapping. These recycled materials find applications in numerous sectors including clothing, carpets, upholstery, and industrial fibers. Recognizing the importance of collaboration among governments, industries, and individuals, we emphasize the need for sustainable PET waste management practices and the promotion of recycled materials. The article also provides information on India's experiences with PET waste management and regulations in other countries. It is important to note that the global production and consumption of PET have increased significantly in recent years, with the packaging industry being the largest consumer of PET. This has resulted in a significant increase in the generation of PET waste, which poses a significant environmental and health hazard if not managed properly. PET waste can end up in landfills, where it can take hundreds of years to decompose, or it can end up in the oceans, where it can harm marine life and the environment. Therefore, the proper management and recycling of PET waste are essential to mitigate these negative impacts. In terms of India's experiences with PET waste management, several initiatives have been implemented to promote the recycling of PET waste. For example, the government has launched the Swachh Bharat Abhiyan campaign, which aims to promote cleanliness and sanitation in the country to promote waste segregation and recycling.

Keywords: polyethylene terephthalate (PET); PET waste; waste management; recycling PET; legal status

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1. Introduction

Polyethylene terephthalate (PET) is a widely used thermoplastic with excellent properties, making it a popular choice for various packaging and single-use plastic products. Its exceptional tensile strength, processability, transparency, thermal stability, barrier properties, toughness-to-weight ratio, and chemical resistance have contributed to its widespread

use [1]. However, the significant consumption of PET has led to a substantial amount of PET waste, especially in the form of single-use packaging. This has raised concerns about the environmental impact of plastic waste, such as marine pollution and landfill accumulation.

To address these concerns, there is a growing global movement to reduce single-use plastics and increase PET recycling efforts. Various strategies have been proposed, including promoting reusable products, exploring sustainable packaging options like bioplastics, implementing deposit–return systems for plastic bottles and other packaging, and investing in recycling programs and infrastructure. These efforts aim to minimize plastic consumption, increase recycling rates, and encourage the adoption of sustainable materials in the packaging industry.

Sustainable packaging solutions have gained momentum in recent years due to consumer awareness and environmental considerations. PET has emerged as a leading candidate in the pursuit of eco-friendly packaging materials due to its recyclability and potential for a circular economy. The ability to collect, process, and transform used PET products into new packaging materials offers a significant opportunity to reduce reliance on virgin resources and minimize waste. PET's transparency also plays a crucial role, allowing vibrant colors and product visibility, enhancing brand recognition, and engaging consumers. Furthermore, PET's exceptional barrier properties protect sensitive contents, extending product freshness and shelf life.

As consumer lifestyles evolve, PET packaging continues to meet the demands for convenience and on-the-go products. Its lightweight nature reduces material waste and provides portability and ease of use for single-serve applications.

This paper aims to discuss effective handling and management techniques for PET packaging waste, focusing on best practices for the collection, sorting, and recycling processes. The objective is to optimize resource utilization and minimize environmental impacts throughout the lifecycle of PET packaging [2–4].

By promoting responsible waste management and environmental stewardship, we seek to inspire individuals, businesses, and policymakers to embrace sustainable packaging solutions. Through education and advocacy, we aim to drive positive change and foster collective efforts in reducing the environmental impact of PET packaging.

Overall, this paper addresses the pressing need for sustainable PET packaging practices, emphasizing the importance of proper waste management and the adoption of environmentally friendly alternatives. By raising awareness and providing guidance, we strive to contribute to a greener and more sustainable future in the packaging industry.

On the other hand, because of its growing consumption and non-biodegradability [5], its waste has increased over the years and poses a severe environmental hazard when discarded after use. PET waste contributes 12% by volume of the world's solid waste, with its volume increasing at an alarming rate [6,7]. PET waste discarding began to pose severe economic and environmental issues with the upsurge in its amount. Economic, environmental, and energy concerns emphasize the large-scale recycling of PET. PET recycling does not only serve as a partial solution to the substantial PET waste problem, but also subsidizes the energy conservation and raw products of the petrochemical industry [8]. The production and consumption of plastic/packaging/PET materials are directly associated with the generation of plastic/packaging/PET waste.

The primary aim of this review article is to explore strategies for reducing and eliminating plastic, packaging, and PET waste through various environmental recycling methods. The objective is to lessen the burden on landfills and mitigate the environmental impact of these materials.

In summary, this paper focuses on several objectives related to PET packaging. Firstly, it highlights the importance of PET as a widely used thermoplastic with excellent properties. Secondly, it discusses effective waste management techniques to address the environmental concerns stemming from PET waste, especially single-use packaging. Thirdly, the paper addresses the challenges and opportunities related to PET packaging, exploring innovative solutions that support a more circular economy and reduce reliance on traditional PET

materials. Furthermore, the paper aims to promote responsible practices in the packaging industry, encouraging the adoption of sustainable alternatives and recycling efforts. By achieving these objectives, the ultimate goal is to contribute to a more sustainable and environmentally conscious approach to PET packaging

2. Production and Consumption of PET

2.1. PET Production

The global polyethylene terephthalate (PET) market is expected to witness significant growth in the coming years. According to market forecasts, the market is estimated to surpass USD 72.88 billion by the end of 2030 in terms of revenue, exhibiting a compound annual growth rate (CAGR) of 6.7% during the forecast period from 2022 to 2030 [9]. PET, which is produced in various forms such as films, bottles, fibers, and resin, is widely recognized as an economically viable option in the packaging industry, particularly for beverages. PET bottles and PET fibers continue to dominate the market, accounting for 30.3% and 63.5% of the total global PET production, respectively, while polyester film and resin account for 6.2 shown in Figure 1 [10–12]. The market's steady growth can be attributed to factors such as increased demand for sustainable packaging solutions, growth in the beverage industry, and the versatile applications of PET in various sectors. As the market progresses, it will be crucial for industry stakeholders to monitor emerging trends and invest in innovative technologies to meet the growing demand for PET products. The size of the global polyethylene terephthalate (PET) resin market was estimated at USD 80.9 million in 2021, and is anticipated to increase from USD 85.11 million in 2022 to USD 127.67 million by 2030, expanding at a CAGR of 5.2% during the forecast period (2023–2030) [13].

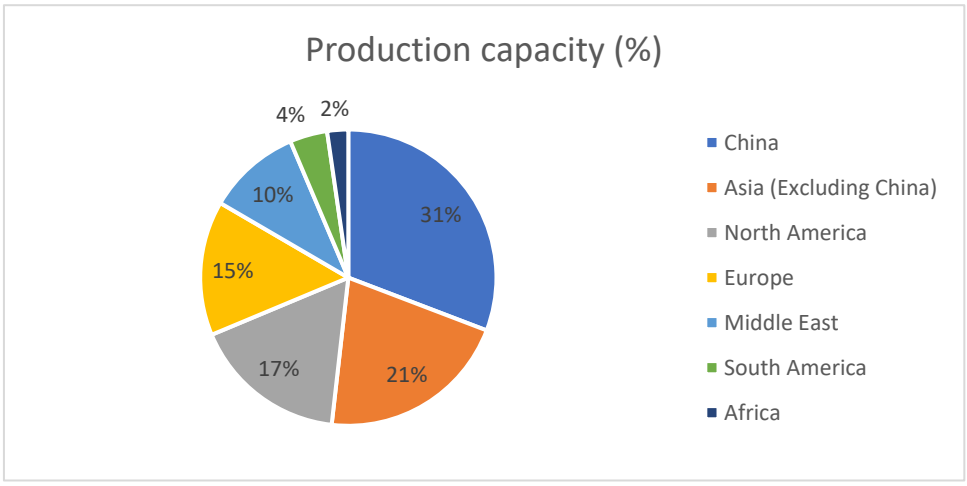


Figure 1. Worldwide PET resin production capacity [11].

2.2. PET Consumption Market

The Middle East is currently experiencing rapid growth in various industries, making it the fastest-growing market globally, with a Compound Annual Growth Rate (CAGR) of 7.15% in terms of value. This growth is primarily driven by two key factors: the increasing manufacturing output of electrical and electronics products, and the rising demand for food and beverage packaging. Saudi Arabia and the United Arab Emirates are projected to remain the largest consumers in the region, with consumption volumes reaching around 47% and 41%, respectively, by 2029. These countries have established themselves as major players in the Middle East market, driven by their economic development and industrial expansion. The growing manufacturing output of electrical and electronics products in the Middle East is contributing to the demand for PET resin. This can be attributed to the region's focus on diversifying its economy and reducing dependence on oil revenue. The production of consumer electronics, such as smartphones, tablets, and

other electronic devices, has been increasing steadily, resulting in a higher demand for PET resin in electrical encapsulation and device manufacturing. The rising demand for food and beverage packaging is fueling the growth of the PET resin market in the Middle East. The region's expanding population, along with changing lifestyles and an increasing preference for convenience-sized products, has led to a surge in demand for PET-based packaging materials. PET offers excellent properties for packaging applications, including its lightweight nature, transparency, and ability to preserve the quality and freshness of packaged products. Overall, the Middle East market's robust growth in the electrical and electronics industry, as well as the food and beverage packaging sector, is driving the increasing consumption of PET resin. Saudi Arabia and the United Arab Emirates are expected to remain key players in the region, driving the market forward with their significant consumption volumes as shown in Figure 2 [14].

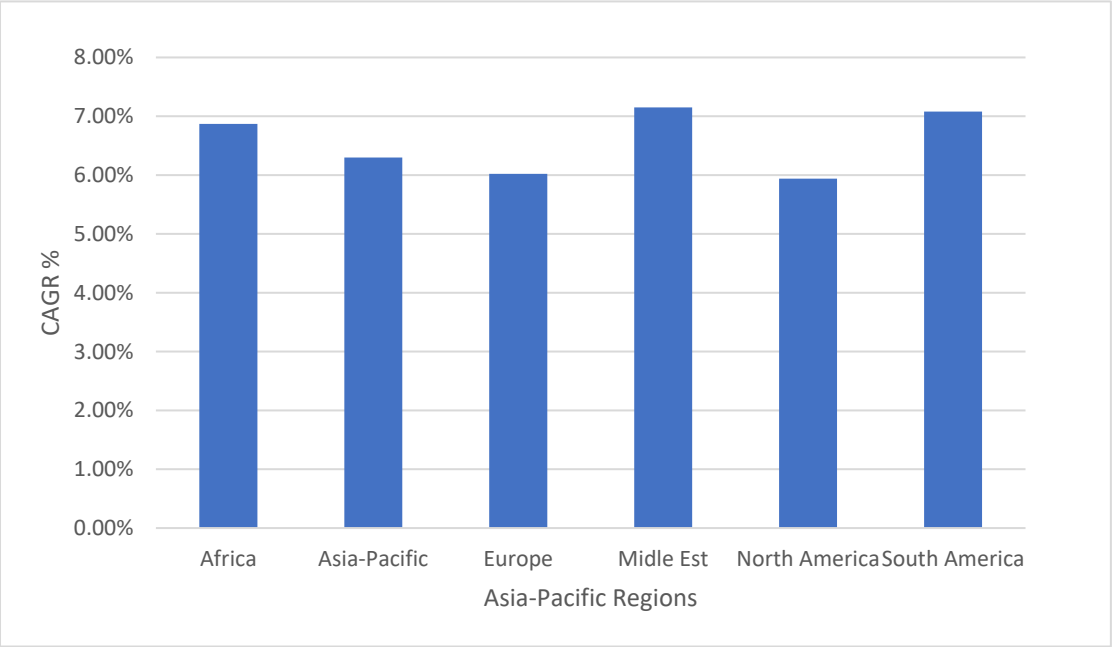


Figure 2. Polyethelene terephthalate (PET) market, CAGR, %, by region, 2023–2029 [14].

PET (polyethylene terephthalate) has a wide range of applications in various industries, including packaging, electrical, and electronics. It is commonly used for packaging foods and beverages, particularly in convenience-sized soft drinks, water bottles, and other packaging forms. Additionally, PET is utilized in electrical encapsulation, electrical devices, solenoids, and smart meters. The packaging sector accounts for a significant portion of the overall PET resin market's revenue, with approximately 96% in 2022. The global packaging industry is the largest end-user industry for PET resin. Factors such as a rising population, increasing income levels, and changing lifestyles contribute to the growth of the global plastic packaging industry. This, in turn, drives the demand for PET resin, especially in end-user segments such as FMCG (fast-moving consumer goods), food and beverages, pharmaceuticals, and others. The production of plastic packaging is expected to increase from 140 million tons in 2023 to around 180 million tons in 2029, reflecting the rising demand in the packaging industry. The electrical and electronics industry is the fastest-growing industry in terms of revenue, projected to register a Compound Annual Growth Rate (CAGR) of 7.88% during the forecast period of 2023–2029. This growth is primarily driven by the expanding consumer electronics market, which is expected to reach a value of USD 1103 billion in 2023. The factors contributing to this growth include the demand for lightweight products, the growth of e-commerce, a focus on sustainability, and higher adoption rates among major consumer product manufacturers. Furthermore, the revenue from electrical and electronics production is anticipated to achieve a CAGR of 6.71% during

the same forecast period. Consequently, the demand for PET resin in the global market is expected to witness significant growth in the near future [15].

3. Scenario of PET and Plastic Waste and Its Recycling

3.1. Global Scenario

Rapid urbanization and increased demand for PET materials, such as plastic packaging, have led to a significant increase in the production and consumption of these materials. This, in turn, has contributed to a rise in the amount of municipal solid waste (MSW) generation. Single-use plastic packaging, which is designed for immediate disposal, is a major contributor to this problem. According to Figure 3 [16], almost 97% of plastic wrapping is thrown away after a single use. India aims to entirely remove single-use plastic by 2022. It is estimated that in 2015, around 158 million tons of plastic material were discarded globally after a single use. This includes plastic packaging, disposable plastic products, and other single-use items. This amount is projected to increase in the coming years due to population growth, urbanization, and increasing consumption. It is important to note that this number is an estimation and might have some variation. Peru has banned the use of single-use plastics in its 76 protected cultural and natural areas, including popular tourist destinations like Machu Picchu, Manu, and Huascarán, as well as in national museums. This move aims to reduce the amount of solid waste generated in these areas, as tourists are a major source of plastic waste, particularly single-use wrapping and PET bottles. At Machu Picchu alone, invitees generate an average of 14 tons of solid waste per day. Plastic packaging accounted for around 50% of the plastic waste generated worldwide in 2015.

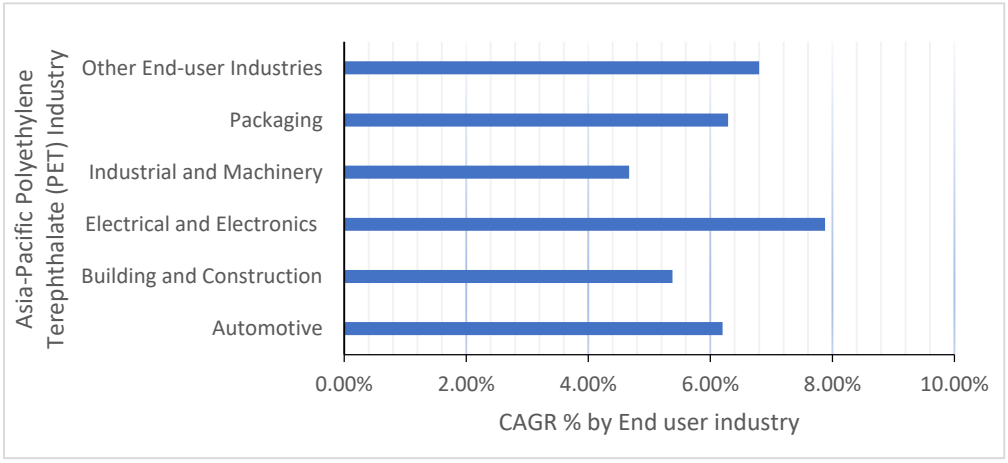


Figure 3. Polyethelene terephthalate (PET) market, CAGR, %, by end user industry, 2023–2029 [16].

In March 2019, the European Union voted to ban the top 10 single-use plastic items found on European beaches by 2021, so as to reduce plastic pollution on beaches and in the ocean. The EU also set a target of 90% of plastic bottles to be recycled by 2025 [17]. Member states were directed to work out the details of the ban before the 2021 deadline. Plastic packaging is a major contributor to coastal litter, accounting for 61% of litter found on worldwide coastlines, at around 300 million tons [18]. In 2015, plastic packaging waste accounted for 47% of the plastic waste generated worldwide. Half of this plastic packaging waste came from Asia, with China being the largest generator of plastic packaging waste worldwide shown in Figure 4. The United States was the largest generator of plastic packaging waste per capita, followed by Japan and the European Union. It is important to note that this information is based on a study from 2015, and the numbers might have changed since then. The Figure 5 depicts the plastic packaging waste generation in 2014, represented in million metric tons (MMt), and the corresponding per capita amount in kilograms (kg) [19].

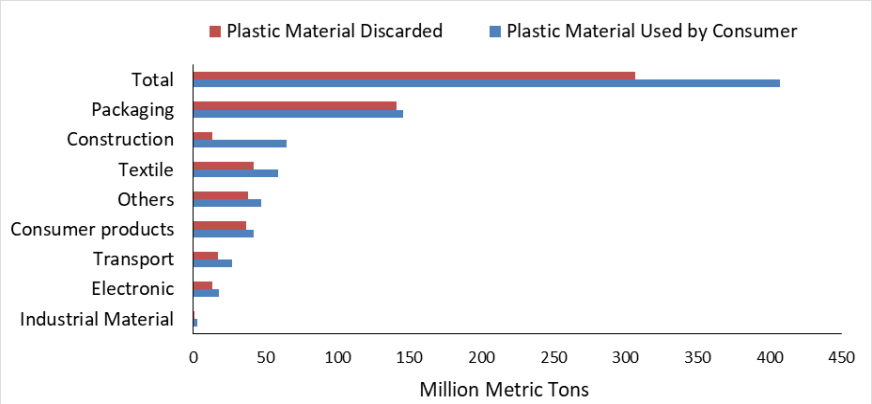


Figure 4. The global plastic material discarded after single use in the year 2015 [19].

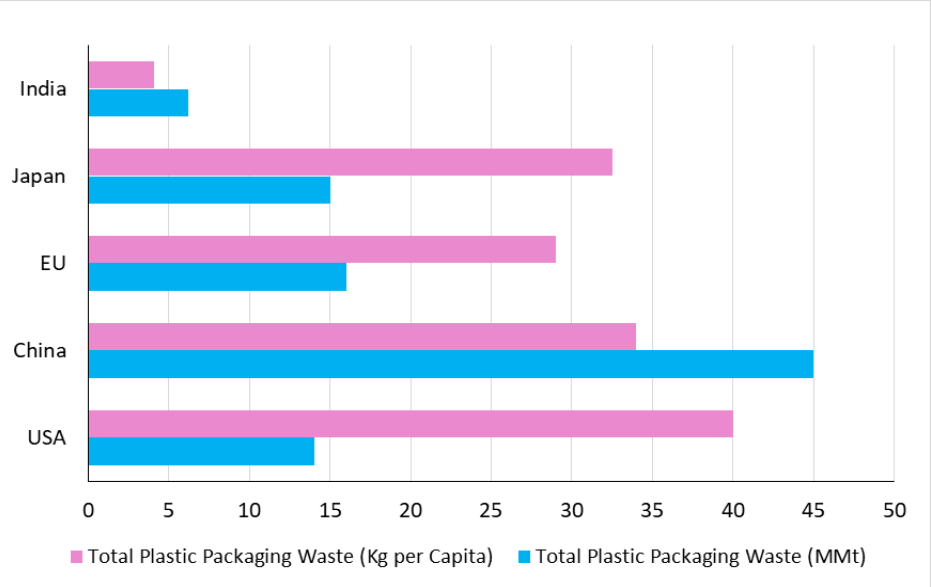


Figure 5. Plastic packaging waste generation in 2014 (MMt) [19].

Plastic products, including those of PET, are often dumped after use and generally form part of MSW. MSW is often a rich source of numerous kinds of recyclable materials such as plastic, paper, glass, and metal. This practice is still in vogue across continents such as the EU, Australia, the USA, India, etc. The general composition of MSW generated in the USA in 2013 is presented in Table 1 [20], which indicates that plastic waste, including PET waste, comprises about 13% of the MSW. Data from a report published by the EPA [21] show that plastic containers and packaging discarding are the primary sources of PET waste in MSW in the USA. Figure 6 shows the MSW generated from some prominent countries [22].

Table 1. Composition of MSW generated in the USA in 2013 [20].

Material in MSW	% of MSW Generated in 2013
Paper	27
Food	15
Yard trimming	13
Plastics	13
Metals	9
Rubber, leather and textiles	9
Wood	6
Glass	5
Other	3

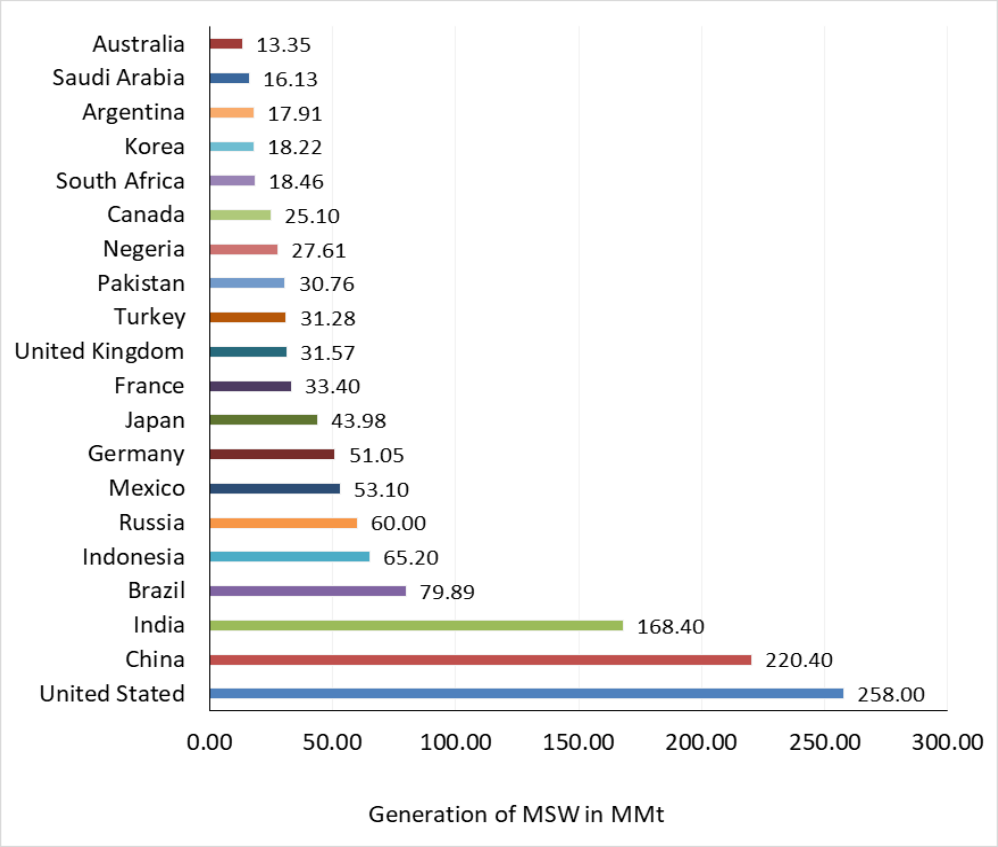


Figure 6. MSW generation in some prominent countries in 2017 [22].

3.2. Indian Scenario

The same as in the USA, PET also forms a significant fraction of the plastic waste in MSW in India [22]. Table 2 shows the average plastic waste generated in some of the metropolitan cities in India [23,24].

Table 2. Plastic waste generated (tons per day) in four metropolitan cities in India [24].

Metropolitan Cities in India	Plastic Waste Generated (Tons per Day)	Population (2011) (Millions)	GDP per Capita 2013 ($)
Delhi	690	11.0	3580
Chennai	429	4.7	1860
Kolkota	426	4.5	1110
Mumbai	408	12.4	1990
Bengaluru	314	8.4	1430

A survey conducted in 60 major cities of India in 2012 [25] revealed that the daily generation of plastic waste in the country was about 15.3 kilotons, or 5.6 million tons, per year. While 60% of the plastic waste was collected and recycled, the remaining 40% went uncollected. This information is from a survey conducted in 2012, and the numbers might have varied since then. Normally, the cities with higher populations and higher GDP per capita create more waste (including plastic). Here, we look at Delhi and Mumbai, with almost the same population, but almost double the amount of waste was created in Delhi. The populations of Chennai and Kolkata are almost one-third that of Mumbai, but they created the same quantity of plastic waste because of the poor management of waste recycling. Several states in India have implemented bans on single-use plastics and have seen positive results. For example, in Maharashtra, a state in India, there was a reported

40% decrease in plastic waste in the seven months following the implementation of the ban. This indicates that the ban has been effective in reducing plastic waste in the area. However, it is important to note that this information is based on a specific case, and the results may vary in other regions or with different types of bans [26].

3.3. Worldwide Recycling Efforts

According to new research, after China's "Green Fence" action plan banned plastic waste imports in 2018, a significant portion of plastic waste exported from the US for recycling was shipped to other countries in Southeast Asia, such as Thailand, Malaysia, and Vietnam. In the first six months of 2018, around half of the plastic waste exported from the US for recycling was sent to these three countries. This indicates that the ban in China caused a shift in the destinations of plastic waste exported from the US. However, it is important to note that this information is based on a specific period, and the current situation may be different [27]. The previous year, the US exported more than 70% of its plastic waste to China and Hong Kong.

The recycling of PET waste is being adopted on a large scale in many countries across the globe to protect the environment and maintain sustainability [28]. Asia's largest PET bottle recycling factory, INCOM Resources Recovery, with an annual recycling capacity of 50 kt, is located in Beijing, China. The used PET plastic bottles are converted into clean PET plastic material for making new bottles through mechanical recycling. The recycling rate of PET bottles in China is reported to be almost 90% [29].

Japan is also involved in recycling waste plastics, where around 77% of plastic waste was recycled in 2010, up from 39% in 1996 and 73% in 2006 [30]. In 2010, Japan recycled 72% of PET bottles, compared with 48% in the EU and 39% in the UK. Further, in 2013, 0.47 million tons of post-use PET bottles were broken down through mechanical recycling. The recycled material was used for sheeting, textiles, industrial materials, and household products such as egg boxes. Further, enormous amounts of rPET are transported to Hong Kong, China, and some other parts of Asia, where it is used for making toys and games.

In collaboration with Alkem Nigeria Limited, a fiber processing manufacturer, Coca-Cola USA started a buyback and recycling scheme for used PET bottles in Nigeria. The joint venture-initiated Nigeria's first bottles-to-fiber recycling plant in 2005, and from 2005 to 2012 the total volume of bottles recycled increased from 135 tons to 6200 tons. This initiative not only helped to reduce plastic waste but also created jobs for an estimated 1500 people. In 2015, the Coca-Cola Company updated its PET bottling plant and created a 100% bio-PET version, aiming to switch entirely to bio-based plastics by 2020 [31].

More and more PET recycling plants are being set up in several countries due to the increase in PET waste. According to a study by the National Association for PET Container Resources (NAPCOR), an initiative was taken up in January 2013 to add four more PET recycling plants in the United States, with an additional capacity of 200 million pounds [32]. Similarly, a state-of-the-art PET recycling plant was built in England in 2012 with an operational capacity of over 50% of the UK's PET waste, and it has been reported to have sorted over 250 million plastic bottles since opening [33]. The plastic/PET waste, co-mingled with MSW, is first sorted by type (metals and plastics), and then further sorted by plastic properties, color, and quality, before subjecting them all to reprocessing.

3.4. Recycling Efforts in India

Recycling PET waste started in India in 1994, but the industry grew slowly. The mostly mechanical recycling process is being adopted to produce rPET fibers. As of 2014, about 25 industries were involved in PET waste recycling. Currently, M/s Ganesh Ecosphere (Shri Shyam Sunder Sharmma founder of the company) is reported to be the largest recycler of PET waste, with an annual capacity of 57,600 tons. M/s Crystic Resins India Pvt. Ltd., Reliance Industries, M/s Dhansari, and M/s JBT are the other major industries involved in this field. Bisleri, one of India's largest packaged mineral water industries, has also started recycling PET bottles [34]. The initiative involves the collection of PET bottles, crushing

them into fine flakes, and then using the same for the manufacture of fibers. The rPET fibers are being widely used for the production of carpets, t-shirts, handbags, window blinds, and other useful products. As already mentioned in Section 5.1 second para reverse vending machines are also being installed in different cities to collect and process used PET bottles.

Sustainable packaging is a growing concern for plastic manufacturers and fast-moving consumer goods (FMCG) companies. Companies like Unilever, one of the world's largest FMCG companies, are taking steps to address this issue. Unilever announced plans to make all its packaging "reusable, recyclable or compostable" by 2025. This goal is a part of Unilever's efforts to reduce its environmental footprint and promote sustainable packaging. Such steps taken by companies are expected to drive the development and adoption of more sustainable packaging solutions in the future.

Western India is the hub of the plastic recycling machinery market, its share being about 46%, followed by North India at 28%, South India at 22%, and East India at only 4%. Gujarat in Western India hosts a significant cluster of plastic recycling machinery manufacturers/suppliers as mentioned in Table 3 [35].

Table 3. Summary of where in India has introduced regulations on plastic/packaging products state-wise [35].

Sr. No.	Name of States	Impact	Year	Importance
1.	Local—New Delhi	Limited because of weak enforcement.	2017	Ban entirely all types of single-use plastics in New Delhi [36].
2.	Local—Himachal Pradesh	Significant decrease in plastic pollution.	2014	The Indian state of Himachal Pradesh has banned the production, storage, sale, use, and distribution of non-biodegradable plastic bags that are less than 70 microns in thickness under the Himachal Pradesh Non-Biodegradable Garbage (Control) Act, 1995. In 2011, the state also introduced a ban on disposable plastic products such as plastic cups, drinking glasses, and plates [37].
3.	Local—Punjab	Information not available.	2016	The state of Punjab in India has implemented a ban on the manufacture, stocking, distribution, sale, or use of single-use containers and plastic carry bags under the Punjab Plastic Carry Bags (Manufacture, Usage, and Disposal) Control. [38].
4.	Haryana	Limited because of weak enforcement.	2010	The state of Haryana in India has also implemented a ban on the manufacture, stocking, distribution, sale, or use of plastic carry bags [39].
5.	Local—Maharashtra	Information not available.	2018	The state of Maharashtra in India has placed a ban on plastic bags less than 50 microns [36].
6.	Local—Karnataka	Plastic bags stay to be both available and commonly used.	2016	The state of Karnataka in India banned manufacturing and sale of plastic bags.
7.	Local—West Bengal	Plastic bags are still commonly used. Implementation is limited.	2001	The state of West Bengal in India banned plastic bags of less than 40 microns and has enforced a blanket ban.
8.	Local—Kerala	Information not available.	2016	The state of Kerala has placed a ban on plastic bags less than 50 microns.
9.	Local—Sikkim	While plastic bags are still typical, majority switched to paper bags or newspapers (66%).	1998	The state of Sikkim in India has placed a ban on purchasing of goods and materials in plastic covers or plastic bags.

4. Unsustainable Disposal Methods of PET/Plastic Waste in Practice

Large quantities of MSW (containing PET and plastic waste) are still being disposed of through unsustainable methods, causing severe environmental damage. These methods are discussed below.

4.1. Disposal in Landfill

Plastic waste dumping in landfills, along with MSW, is a widely adopted practice, despite knowing that it leads to the wastage of valuable land resources, and with the awareness that is not considered a sustainable waste management practice. Besides occupying a vast area of land, it also generates odors and aerosols, causes visual disruption, and releases harmful chemicals and gasses through escape as leachates from landfills. Although the relative proportion of land occupied by plastic/PET waste is low in comparison to that of MSW, the damage caused to the environment by the same is enormous due to its non-biodegradable characteristics. Plastics/PET decompose very slowly and inhibit the breakdown of useful biodegradable materials from the soil. Despite this, the continued practice of dumping in landfills may be due to a lack of sufficient funds, and technical know-how, required to implement sustainable methods.

The average proportion of MSW dumped in landfills in the European Union is about 38%. Some of the leading European countries have stopped landfilling, or only a small proportion (up to 19%) is dumped into landfills, while the rest is diverted for recycling/compositing, or for waste-to-energy generation [40]. Australia also continues to depend on landfills to dispose of municipal solid wastes. Tata Energy Research Institute (TERI), India, estimated that about 1400 sq. Km of land area (equivalent to the city of Delhi, India) would be required by 2047 for dumping municipal waste in India [41].

Th landfill deposition of MSW is more prevalent in the USA, where about 68% of MSW is dumped in landfills. This is attributed to opposition by environmental groups to adopting waste-to-energy processes. However, a large number of landfills (560 out of 1900) are implementing technologies to capture landfill gas (methane) and produce electricity, which is recognized as a renewable energy source. Although it is a welcome step, only about a third of the potent greenhouse gas is converted into electricity in reality.

4.2. Burning in an Open Environment

Burning PET waste mixed with plastic waste in the open environment is also a hazardous process. It is considered an inappropriate way of managing plastic waste, because of the emission of toxic gasses produced from the decomposition of plastic/PET molecular chains and additives. During the process, halogens in the plastics fraction form volatile metal halides, which, through catalytic effects, aid in the formation of dioxins and furans [42]. The adverse environmental impacts due to the incineration of plastic waste in the open atmosphere include the generation of airborne particulates and greenhouse gas emissions. Therefore, the open burning of PET and plastic waste is not practiced in many European countries, and all the waste is utilized in the recycling processes. The government of India also enforced a ban on the open burning of plastic waste [43]. The open burning of plastic and other solid waste is also prohibited in Sri Lanka, and the same is considered a punishable offense there [44].

4.3. Littering

Littering is another inappropriate way of disposing of plastic/PET waste. Such waste, which fails to reach landfills or incinerators, is identified as the cause of manifold ecological problems, such as the choking of water bodies, an impediment to the growth of flora and fauna, etc. The dumping of plastic waste into water bodies such as rivers or oceans contributes to the deaths of millions of seabirds, thousands of marine mammals, and countless fish every year [45]. The city of Mumbai, India experienced tremendous monsoon flooding in the year 2005, resulting in around 1000 deaths [46], and the same was blamed on plastic bags that choked the gutters and drains, preventing rainwater from draining

through underground systems. A similar tragedy occurred in 1988 and 1998 in Bangladesh, which led to the banning of plastic bag usage in 2002 [47]. Sri Lanka and other countries adopted a ban for similar reasons. Mauretania imposed a ban on plastic bags as cattle were getting sick from eating plastic bags. Indonesia, the world's second-biggest plastics polluter after China, has pledged to reduce plastic waste emission into the ocean by 75% by 2025. According to BBC News, South Africa and Cameroon have recently joined other countries to declare a tax on the use of thin bags to prevent the contamination of Africa's fields and cities.

5. Environment-Friendly (Sustainable) Methods of PET and Plastic Waste Management

Worldwide efforts are in progress to discourage practicing the above unsustainable disposal methods and develop environment-friendly (sustainable) methods to manage PET and plastic waste, which also results in the generation of some useful products.

Thermo-plastic wastes such as HDPE, PP, etc., are being used in bitumen road construction [48]. It was reported that about 1 ton of plastic waste in molten form is mixed with 5 tons of bitumen to construct 1 km of road. The usage of PET waste as a polymeric admixture to bitumen was attempted at a temperature of 200–220 °C. The same resulted in an increase in Marshall Stability by up to 76% at a dosage of 5.3% PET waste. An increase in the density and flow value of the mix was also reported [49]. Crushed PET waste and vehicle tire waste were used as fine aggregates in road construction [50,51].

Recycling PET and plastic waste is attracting worldwide attention as a sustainable option to manage the same. However, to implement these methods, it is necessary first to segregate PET and plastic waste from MSW (for waste-to-energy conversion), and segregate PET waste from plastic/PET waste (for material recycling).

5.1. Collection of PET and Plastic Waste from Source

To promote the collection of plastic waste before dumping it into MSW, people worldwide are encouraged to segregate their waste at the source as recyclable and non-recyclable waste, and deposit the same in separate bins placed at the roadside. Placing colored bins (such as blue, green, and yellow) at convenient locations in which such waste can be deposited is being widely adopted in many countries, such as the UK, Singapore, Germany, etc. Such a system is also practiced in many cities in India, such as Chennai, Mumbai, Bengaluru, Delhi, and Kolkata. The colored bins are also being made available to individuals on a yearly rent basis for the deposition of plastic waste, and these are collected once a week. An automated underground pipe system has been installed in some of the cities of the world, through which the waste deposited in colored bins in residential areas, business premises, town centers, hospitals, and airports is transported with the help of air (at a velocity of about 70 km/h) to a centralized processing plant. One such system is in operation in the city of Gandhinagar, Gujarat, India. However, the old practice of manual door-to-door waste collection on pneumatic vehicles is still in vogue in many cities of India.

Reverse vending machines, which accept used beverage cans and PET bottles and give cash in return, are in use in countries like the USA, Germany, Australia, China, etc. Sometimes, monetary incentives (in terms of mobile recharging, travel tickets, movie tickets, parking tickets, etc.) are being offered to encourage people to place used plastic bottles in collection bins. In India, the first reverse vending machine, which can accept and crush up to 500 bottles in a day, was set up at Church Gate Railway Station in Mumbai, India, on June 2015. Users will get an instant "reward" when used containers are fed into the machine, thus motivating them towards repeated use. When the device accepts the bottles, three options will appear on the screen; rewards, mobile recharge, and a discount from an outlet with which the machine provider has ties for concessions. The user can select any of the options, and a printout for the same will be issued. Bisleri, one of the largest bottled water manufacturing companies in India, and Inorbit Mall jointly started a PET bottle collection center in Inorbit Mall, Vashi, and Mumbai, India in February 2012. It is India's first ever plastic (PET) bottle collection and recycling machine (with no incentive).

5.2. Separation of Plastic Waste from MSW

5.2.1. Electrostatic Separator

This method is frequently used to separate directing and non-conducting constituents in MSW, and is usually applied to isolated aluminum or copper from plastics or paper [52]. Furthermore, a technique that uses eddy currents is also employed to separate plastic particles from metal and plastic mixture. These procedures are appropriate only to separate good conductors, such as metallic particles, from dielectrics, such as plastics. However, this method is unsuitable for separating dielectric particles such as mixed plastic combinations.

5.2.2. Triboelectric Separation

Triboelectric separation is a type of electrostatic separation that utilizes frictional charging. Its use for the separation of plastics is a relatively new approach. In this technique, electric charges are imparted to the particles of two polymers in a mixture, and then they are separated by passing through an external electric field [53]. The deposition of positive or negative electric charges on a polymer depends on its ability to hold or lose electrons. A material with a higher affinity for electrons gains electrons and gets negatively charged, whereas a material with a low affinity loses electrons and gets positively charged [54]. An air cyclone is employed as a charging device to produce a higher frictional speed, and a triboelectric cyclone separator has been developed, which has been successfully tested for separating plastics in the laboratory.

5.2.3. Air Separator

This method is common in recycling facilities to separate different materials from a waste stream, such as plastic bottles from aluminum cans. The method is based on the principle of density, where materials with different densities are separated by controlling the airflow generated by a fan. The process starts with the waste stream being fed into the separator. The measured airflow produced by the fan splits the waste into light and heavy fractions, with the light fraction being extracted upwards and the heavy fraction being separated into a second conveyor [55–57]. The less-heavy fraction then reaches a rotary valve, where the rotor reduces the airspeed and the fraction is discharged onto another conveyor. This separation method is efficient and cost-effective, as it allows for separating different materials in a single step, making it easier to recycle the different materials. However, it is important to note that the separation process's effectiveness depends on the waste stream's specific characteristics, such as the size and density of the materials.

5.3. Separation of PET Waste from Plastic Waste

The waste plastic consequently collected directly (as described in Section 4.1) or separated from MSW (as described in Section 5.2) is additionally separated from discrete PET in the rest of the plastic waste. There are various methods for separating PVC and PET from plastic waste, as they often look similar and are problematic to differentiate. One method is the use of spectroscopy methods, which employ different types of spectroscopy, such as FTIR and XRF, to identify different types of plastics/polymers. Another method is the use of dry separation techniques, which utilize different physical properties such as the density, size, and shape of the materials to separate them. Air separation, eddy current separation, and electrostatic separation are examples of dry separation techniques. Wet separation techniques are also employed for separating PVC and PET from plastic waste. The liquid medium is used to dissolve or soften certain plastics, making separating them easier. The disadvantage of wet separation techniques is that they require a post-sorting process for re-use or discharge, expensive reagents, and the drying/dewatering of the plastics extracted from the process [58]. It is important to note that the separation process's effectiveness depends on the waste stream's specific characteristics, such as the size and density of the materials, and the type of separation technique used (Table 4).

Table 4. PET waste separation from plastic waste.

Techniques	Tools/Process		Different Types of Recovered Materials	References
Dry Separation technique	Conveyor, resin/color detector, and air-jet ejector		PET and PVC	[59–66]
	IR method for detection	FTIR		
		Acoust-optic tunable filter		
		Optical filter		
		IR with a diffraction grating		
	Raman spectroscopy		PET and PVC	[67]
	InGaAsP laser diode		PET and PVC	[68,69]
	Air separator		PET and PVC	[57]
Wet Separation techniques	Flotation		PVC/PET	[70–72]
			Seven kinds of plastics, including (PVC, PET, PS, ABS, etc.)	[73]
	Sink–float method and selective Flotation technique		HDPE, PP, PET, PVC, PS, and ABS.	[74–77]

6. Methods of Management of Plastic Waste

6.1. Waste-to-Energy Conversion

6.1.1. Pyrolysis

Thermal depolymerization or pyrolysis is a process in which plastic/PET waste is heated to high temperatures (typically between 400 and 500 °C) in the absence of oxygen (in an oxygen-free environment) to break down the polymer chains and convert the plastic into smaller molecules. These smaller molecules can then be converted into various products such as gases (syngas), liquids (pyrolytic oil), and solids (char).

The syngas produced from this process can be used as a fuel source in boilers or engines to generate electricity. The pyrolytic oil can be used as a fuel for heating or feedstock for producing chemicals and new plastics. The solid char can also be used as a fuel or feedstock to produce activated carbon [78,79].

The main advantage of this process is that it allows for the recovery of energy from plastic waste and the production of new raw materials, which can be used to make new plastics, thus reducing the dependence on fossil fuels and the amount of plastic waste in the environment. However, this process is still in the research phase, and commercial applications are limited. The process is also expensive, and there is a need for more research to improve its efficiency and reduce the cost of the process [80,81]. It is considered green technology, as it does not contaminate water and the environment. Plasma Pyrolysis Technology (PPT) is a type of closed environment burning technique primarily used to burn medical waste. Still, it can also be used to burn plastic waste at high temperatures, such as 850 °C. A plasma-based pyrolysis system has been designed and put into use in the state of Gujarat, India for INR 1.2 million (Bhasin, 2009) [82].

A project entitled "Plastic Waste Disposal using Plasma Pyrolysis Technology" was funded by the Central Pollution Control Board (CPCB) and undertaken by the Facilitation Centre for Industrial Plasma Technology (FCIPT), Gandhi Nagar (Gujarat). The Institute for Plasma Research received funding to investigate the technology of plasma pyrolysis with economic support from the Department of Science and Technology (DST), and the New Delhi and Technology Information, Forecasting & Assessment Council (TIFAC). The study was supplemented by applying different kinds of waste plastic such as multilayer, metalized packaging, thin carry bags, etc. Throughout the experimentation, pollutant emissions such as dioxins, furans, particular matter (PM), oxides of nitrogen, and carbon monoxide were

observed (CPCB, 2016) [83]. In this method, the high maximum temperature was reached using a plasma torch in an oxygen-starved environment, which destroys plastic in an eco-friendly and efficient manner.

M/s Envac have installed waste treatment plants in many countries across the globe based on the pyrolysis process to produce biogas, liquid fuel, and bio-fertilizer. One such system has been in operation in the city of Gandhinagar, Gujarat, India, since April 2015. The controlled burning of waste to produce (electrical) energy is also being practiced worldwide. India's first commercial waste-to-energy plant with a handling capacity of 1300 tons of MSW per day and a production capacity of 16 MW energy has been in operation in Delhi, India, since 2010 (Westinghouse Plasma Corporation, 2014) [84].

6.1.2. Gasification

Gasification is the controlled burning of PET and plastic trash at temperatures between 600 and 800 °C in the presence of air or occasionally purified oxygen, with the latter approach being more expensive. Syngas, a combination of gases created through this process, is the initial result, and can be utilized as a fuel alternative to natural gas or as a source of raw materials for the manufacture of petrochemicals. Anke-Brems et al. (2013) have discussed the many technologies that are involved in the process, and how frequently a fluidized bed gasifier is employed for the purpose [85,86]. It should be noted that PET waste was also included in the plastic waste used in the operations above. Two plants built by M/s Westinghouse Plasma Gasification, each with a 1.6 MW capacity and able to consume roughly 72 tons of garbage per day [87], are located in the Indian state of Maharashtra.

6.2. Material Recycling

6.2.1. PET Recycling Techniques

The first report on recycling PET bottle waste came from the USA in 1977 [88], and since then, numerous investigations on PET recycling techniques have been conducted [89–91]. Used PET is being recovered at a steadily higher rate. With a rate of about 19.5%, PET leads the list of materials recycled from all solid plastic trash [21].

Mechanical Recycling

Mechanical recycling, also known as material recycling, primarily involves the washing of PET waste, followed by its crushing and grinding to reduce its size into flakes, re-extrusion into fibers, and the processing of the same for the production of new PET goods. There are two mechanical recycling methods that are currently in vogue for the production of fibers from PET waste:

1. A more common process for turning flakes into fibers is direct extrusion. Molten PET is extruded into a mold during the extrusion molding process, where it cools and solidifies to take the shape of the mold. For the production of huge products, PET extrusion molding is used. PET can be easily produced as an extruded material for bottles and jars;
2. The melt-extrusion process performed at 280 °C, where PET flakes are extruded into pellets or granules and then melt-extruded into fibers for extrusion molding (Bottle to Bottle PET recycling). It is worth noting that PET can be easily produced in the form of extruded material for bottles and jars, and blowing manufacturing can also be used for jars. This suggests that the same manufacturing process can be used for both bottles and jars made from PET. Technologies and plants are also available for the bottle-to-bottle process, in which PET bottle flakes are directly converted and then blown to make a bottle in an integrated system.

Chemical Recycling

Chemical recycling involves converting the PET chain by chemical processes into oligomers and other compounds. This process can be divided into two main categories: de-

polymerization and functionalization. Depolymerization consists in breaking down the PET chain into its monomers, which can then be used to produce new PET. Functionalization, on the other hand, involves chemically modifying the PET chain to produce new chemicals with different properties and applications [92–96]. One example of depolymerization is the process of methanolysis, in which PET is dissolved in methanol and heated to produce a mixture of terephthalic acid and ethylene glycol, which can be recycled to produce new PET. Another example is the process of glycolysis, which involves using a glycolysis agent to break down the PET chain into its monomers.

Chemical recycling can help reduce plastic waste's environmental impact, as it allows for the recovery and reuse of plastic materials, rather than relying on the traditional mechanical recycling process. However, it is an expensive process and requires specialized equipment and skilled personnel. It also poses a risk of pollution and the generation of harmful by-products.

In comparison to previous review papers on the management of polyethylene terephthalate (PET) plastic waste, our study offers several distinct contributions. While existing reviews have provided valuable insights into PET waste management practices, they often focus on general waste management techniques without a specific emphasis on PET waste, or lack a comprehensive analysis of regulatory frameworks and applications of recycled PET waste. In contrast, our study specifically concentrates on mechanical and chemical recycling methods for PET waste, exploring their advantages, limitations, and potential applications. Additionally, we delve into the rules and regulations implemented in different countries, shedding light on the varying approaches to PET waste management. Moreover, we examine the wide range of applications for recycled PET waste across industries such as textiles, packaging, and construction. These unique aspects differentiate our work from previous reviews and contribute to a more comprehensive understanding of PET waste management strategies [97].

Glycolysis is a chemical recycling process that involves the breaking down of PET into its constituent monomers, which are then used to produce new PET. This process typically involves heating the PET with a catalyst and a small amount of glycol, such as ethylene glycol or diethylene glycol. The glycol acts as a solvent and a reactant, helping to break down the PET and facilitate the formation of new monomers. The resulting monomers can then be purified and used to produce new PET. This method is found to be more environmentally friendly than traditional mechanical recycling methods (Table 5), as it allows for a greater degree of control over the final product and reduces the need for virgin raw materials. However, it is also more complex and costly, requiring specialized equipment and expertise [98].

Table 5. Chemical recycling techniques of PET waste.

Chemical Recycling Techniques	Reactant	References
Glycolysis	Ethylene glycol or diethylene glycol or propylene glycol dimethacrylated glycolysate	[99–104]
Hydrolysis	Water or acid or alkali	[105–108]
Methanolysis	Methanol	[109]
Aminolysis	Amine	[110–113]
Ammonolysis	Ammonia	[114]

In glycolysis, PET waste is chemically reacted with a diol, such as ethylene glycol, at high temperatures. The reaction breaks down the PET polymer into its constituent monomers, ethylene glycol, and terephthalic acid. These monomers can then be purified

and used as raw materials to produce new PET or other chemicals. The glycolysis of PET was first described in a patent in 1965 [115], and it involves the transesterification/glycolysis of a PET molecule with glycol and conversion of the same into a BHET molecule in the presence of transesterification catalysts. In this process, PET degradation is carried out using EG [116], DEG [117], propylene glycol, and di-propylene glycol [118] (Table 6). However, like glycolysis, a partial depolymerisation reaction resulting in an intermediate product, i.e., BHET and oligomers, can be used directly to produce new PET. It requires mild reaction conditions, such as atmospheric pressure and a temperature range of 180–250 °C. Therefore, attempts have been made for enhancing the rate of glycolysis and BHET monomer yield by use of efficient catalysts and the optimization of the reaction conditions, and these exertions have resulted in enhancements in BHET monomer yield and reaction time from 65% over 8 h to around 90%, and a reduced reaction time of about 30 min [118–120]. The most intensively studied method for increasing the glycolysis rate is the use of transesterification catalysts. Metal-based catalysts stimulate glycolysis reaction mechanisms [121,122].

Table 6. Glycolysis de-polymerization of PET by numerous reactions (Raheem et al. 2019) [6].

Catalysts	EG/PET Ratio	PET/Catalyst Wt. Ratio	T °C	Time Minutes	BHET Yield (%)	Reference
Zinc Acetate Lead Acetate Sodium Carbonate Sodium Bicarbonate	6:1 (m/m)	0.005	190	480	62.51 61.65 61.5 61.94	[123]
Zinc Acetate Titanium Phosphate	2.77:1 (m/m)	0.003	200	150	62.8 97.5	[124]
Zinc Acetate	5:1 (*w*/*w*)	0.01	196	180	85.6	[125]
Acetic Acid Lithium hydroxide Sodium sulfate Potassium Sulfate	6:1 (m/m)	0.005	190	480	62.42 62.50 65.72 64.42	[121]
B-zeolite γ-zeolite	6:1 (m/m)	0.01	196	480	66 65	[126]
Magnesium Chloride Ferric Chloride Lithium chloride Didymium Chloride Zinc Chloride	10:1 (m/m)	0.005	197	480	55.67 56.28 59.46 71.01 73.24	[122]
Sodium carbonate	2.45:1 (*w*/*w*)	0.01	196	60	78.94	[127]
SO_4^{-2}/ZnO-TiO_2	5.63:1 (*w*/*w*)	0.003	180	180	91.9	[128]
ϒ-Fe_2O_3	3.7:1	0.0005	300	60	>90	[129]
Zn $(OAc)_2$	6:1	0.002	208	150	85	[130]
$Bmim_2$	4:1	0.2	175	90	95.7	[131]
(Mg-Zn)-Al	10:1	0.01	190	180	75	[132]
Nano ZnO	4:1	0.0005	190	80	90	[133]
Zinc Acetate TNT (Titanate Nanotubes)	4:1 4:1	0.0033 0.0033	196 196	120 120	82.6 76.7	[134]

6.3. Methods of Management of PET Waste

The management of PET waste involves various methods and strategies to minimize its environmental impact and promote sustainable practices. Here are some common methods of PET waste management:

1. Recycling—Recycling is a key method for managing PET waste. PET bottles and other PET products can be collected, sorted, and processed through mechanical or chemical recycling methods to produce new PET products or other useful materials. Recycling helps to conserve resources, reduce energy consumption, and divert PET waste from landfills;
2. Waste separation and collection—Effective waste separation and collection systems are essential for proper PET waste management. Establishing recycling programs, providing separate bins or containers for PET waste, and educating the public about the importance of recycling are crucial steps. Communities, businesses, and governments can work together to implement efficient waste collection systems;
3. Extended producer responsibility (EPR)—EPR is an approach whereby producers or manufacturers take responsibility for the entire lifecycle of their products, including proper disposal and recycling. By implementing EPR programs, manufacturers of PET products can design their packaging to be more recyclable, support recycling infrastructure, and take part in the collection and recycling of PET waste;
4. Waste-to-energy conversion—In cases where PET waste cannot be effectively recycled, waste-to-energy conversion methods can be considered. Technologies such as incineration or gasification can convert PET waste into energy sources like heat or electricity. However, it is important to ensure that these processes are conducted in an environmentally sound manner, and meet appropriate emissions standards;
5. Education and awareness—Educating the public about the importance of proper PET waste management is crucial. Promoting awareness campaigns, providing information on recycling practices, and encouraging responsible consumer behavior can help in reducing PET waste generation and increasing recycling rates;
6. Reducing single-use plastics—Addressing the root cause of PET waste involves reducing the consumption of single-use plastics. Encouraging the use of reusable alternatives, promoting sustainable packaging solutions, and supporting initiatives to phase out or limit single-use plastics can significantly reduce the amount of PET waste generated;
7. Research and innovation—Continuous research and innovation are important for finding new and improved methods of PET waste management. This includes developing advanced recycling technologies, exploring new uses for recycled PET materials, and finding ways to optimize waste management processes.

Implementing a combination of these methods, along with policy support and collaboration between various stakeholders, can contribute to the effective management of PET waste and the transition to a more sustainable circular economy.

7. PET Recycling Techniques

PET waste can be recycled using both mechanical and chemical recycling techniques. Mechanical recycling involves collecting and sorting PET waste, followed by shredding, washing, melting, and reprocessing the waste into new plastic pellets or fibers. This method is widely used and helps to produce various PET-based products. On the other hand, chemical recycling utilizes different processes such as glycolysis, hydrolysis, methanolysis, or solvolytic depolymerization to break down PET waste into its monomer building blocks, or other valuable chemicals. Chemical recycling offers the potential to recover high-quality monomers for PET production and address challenges associated with complex PET products (Table 7). Continued research and development efforts are being made to optimize both mechanical and chemical recycling techniques for PET waste recycling.

Table 7. Different glycolysis methods for PET recycling.

S. No	PET Glycolysis Methods		References
1	Kinetics of PET waste glycolytic degradation.		[135–143]
2	Theoretical and simulation research on PET glycolysis depolymerization.		[144]
3	Microwave glycolysis depolymerization of PET.		[116,143,145]
4	PET glycolysis depolymerization catalysts	Organometallic catalysts (heavy metal salt)	[119,127,136,146,147]
		Non-toxic metal salt (ionic liquid)	[147–149]
		Deep eutectic solvent catalyst	[150]
		Regenerable or recoverable catalysts	[151]
		Large-surface-area catalysts	[129]
		Other types of catalysts	[152]

7.1. Mechanical Recycling

Mechanical recycling is the most common and widely employed method for recycling PET waste. It involves several steps:

1. Collection—PET waste, such as used PET bottles, is collected through recycling programs, waste management systems, or dedicated collection points. The proper collection and segregation of PET waste are crucial for effective recycling;
2. Sorting and cleaning—Collected PET waste undergoes sorting to separate it from other types of plastic and non-recyclable materials. The sorted PET waste is then thoroughly cleaned to remove contaminants like labels, caps, and residual liquids;
3. Shredding and granulating—The cleaned PET waste is shredded into smaller pieces or flakes. The flakes are then further processed into granules or pellets. Shredding and granulation increase the surface area of the PET material, making it easier to handle during subsequent processing;
4. Melting and purification—The PET flakes or granules are melted down to a liquid state in high-temperature extruders. During this process, any remaining impurities, such as dyes or additives, are filtered or removed. The purified molten PET is then cooled and solidified;
5. Reprocessing—The solidified PET material is usually cut into small pellets or chips, which can be used as feedstock in various manufacturing processes. These processes can include injection molding, blow molding, or extrusion to produce a wide range of PET-based products, such as fibers, films, sheets, bottles, containers, and packaging materials.

7.2. Chemical Recycling

The following Table 7 represents various methods of glycolysis used for the treatment of polyethylene terephthalate (PET) plastic waste. This table highlights different approaches used in glycolysis, such as kinetics of PET waste glycolytic degradation, the microwave glycolysis depolymerization of PET, etc., and Table 8 compares them based on key parameters including reaction conditions, catalysts used, reaction time, yield of monomers and temperature. The table provides a comprehensive overview of the different methods of glycolysis, enabling a comparative analysis of their effectiveness and feasibility for PET plastic waste management.

Relative Advantages of Glycolysis over Methanolysis and Hydrolysis

Glycolysis of PET is an area of widespread research because of the advantages of this process over methanolysis and hydrolysis, which include its suppleness, simplicity, low capital costs [153], eco-friendliness, and high yield. It also has a lower reaction time, and the process can be simply adapted to the conventional plants used for PET production. It stands out as the best PET recycling process over the other methods for the reason that it is

carried out in an extensive series of temperatures from 180 °C to 240 °C [118], and achieves the uppermost proficiency and eminence of the product when a catalyst is used [154,155]. Another additional benefit of glycolysis is that the BHET can be mixed with fresh BHET, and the combination can be used for other (DMT-based or TPA-based) PET production lines [105,115].

On the other hand, hydrolysis is comparatively easy compared to glycolysis and methanolsis. Among the three depolymerizing agents used in these three processes, i.e., water (hydrolysis), methanol (methanolysis), and ethylene glycol (glycolysis), water is the weakest nucleophile [8]. The other disadvantage of hydrolysis is the use of higher temperatures (200–250 °C) and pressures (1.4–2 MPa), besides a longer duration needed for depolymerization. Commercially, hydrolysis is not widely used to produce food-grade recycled PET because of the cost associated with the purification of the TPA produced during the process [140].

The main disadvantage of the methanolysis method is the high cost associated with the separation and refining of the mixture of the reaction products (glycols, alcohols, and phthalate derivatives). Furthermore, the water formed during the process causes a toxic effect on the catalyst, also causing the formation of various azeotropes. Also, with the existing inclination to use TPA, instead of DMT, as the raw material for the production of PET, the DMT produced by methanolysis must to be converted into TPA, which significantly adds to the cost of the methanolysis process [156].

Mechanical vs. Chemical Recycling.

The relative advantages and disadvantages of mechanical and chemical recycling are presented in Table 8.

Table 8. Advantages and disadvantages of recycling methods.

Mechanical Recycling	
Advantages	**Disadvantages**
Recycling PET by melt reprocessing is relatively simple, requires lower investments, utilizes established equipment [157,158], is flexible in relation to feedstock volume, and has little adverse environmental effect.	(a) The foremost disadvantage faced in the melt reprocessing of any PET is a reduction in melt viscosity, which is caused by thermal and hydrolytic degradation [127]. (b) Melt reclaiming can produce cyclic and linear oligomers, which can affect the final product's features, such as printability or dyeability [159]. (c) Impurities such as polyvinylidene chloride (PVDC), PVC, glues, paper, ethylene-vinyl acetate (EVA), etc., produce acidic mixtures, which catalyze the hydrolysis of the PET's linkages of ester during thermal reprocessing [160]. (d) The yellowing of recycled post-consumer PET is another disadvantage. It could be due to intra-molecular cross-linking. Yellowing is sometimes a significant hindrance to the production of transparent recycled PET products.
Chemical Recycling	
Advantages	**Disadvantages**
(a) It does not involve the use of huge machines. (b) It may be more cost-effective than mechanical recycling. (c) Compared with mechanical recycling, chemical recycling conforms more to the principles of sustainability because it produces original raw materials.	(a) The initial developing cost can be higher. (b) To be economically viable, chemical recycling methods need to be on a larger scale. (c) No published reports are available on the utilization of chemical recycling on an industrial scale.

8. Applications of Recycled PET (rPET) Products

Recycled PET goods have found numerous uses and are being employed in place of virgin PET. Table 9 indicates broad areas of applications of rPET [161], and as may be seen, large quantities of rPET are used to produce fibers.

Table 9. Application of rPET flakes.

Name of Product	Applications (%)
Fiber	38%
Food and Beverage Bottles	25%
Sheet and Film	24%
Strapping	7%
Non-food Bottles	4%
Other	2%

Table 10 presents some details of the application areas where products obtained from PET recycling are being used worldwide.

Table 10. Applications of products obtained from PET recycling.

Products from PET Recycling	Applications	References
rPET Fiber	• Cement concrete pavements as reinforcement: increases flexural strength and modulus of elasticity, and reduces plastic and drying shrinkage. Can also be used to improve structural properties depending on the size and diameter of the fiber • Textile: automobile seats, homes and office furniture, car roof. • PET staple fibers: carpets and rugs, fiberfill, and nonwoven fabrics.	[162–168]
rPET Resin	• Construction: for the preparation of polyester polymer concrete with high compressive strength, flexural strength, and modulus of elasticity for use in repair works, joint, and crack filling. • Textile: automobile seats, homes and office furniture, car roof. • PET bottle manufacturing • Food and fruit containers • Cosmetic containers • Packaging materials • Enamel paints • Aqueous coating compositions • Epoxy-based paint	[169]
rPET Pellets	• As aggregates in cement concrete	[170,171]
rPET flakes	• As aggregates in cement concrete and polymer concrete • Bottle • Shoes and backpacks • Polar jackets	[172–178]
Activated Carbon or Activated Charcoal	• Industrial application: in the metal finishing field • Environmental application: carbon adsorption has many applications in eliminating pollutants from air or water streams • Agricultural application: used as a pesticide, used in organic winemaking, etc.	[179]
Hydrocarbon Liquid Fuel	• Transportation • Electric power generation.	[180]
Polyester polyols	• Coating application on mild steel	[181,182]
Polyurethane	• Tennis grips • Automobile part • Wheels • Rigid-hulls boats • Building insulation • Fridges and freezers: excellent insulators, low energy consumption, cost-effective • Wheels • Adhesives: especially as woodworking glue • Construction of sealant and fire stopping	[183]
Polyurethane Foam	• Flexible foam: bedding, furniture, and automobiles • Rigid foam is used as an insulation material	[184]
Urethane Oil	• Used as a varnish (wood surface coating material)	[185]

9. Governmental Regulations for the Management of PET and Plastic/Waste

Keeping in view the growing volumes of plastic waste, concerted efforts were initiated long ago to manage plastic waste in many countries by formulating legal guidelines. As PET waste is a part of plastic waste, no separate guidelines for PET waste have been made. The Bureau of Indian Standards (BIS) issued an Indian Standard IS: 14534 in 2016 recommending different ways of plastic waste recycling, and suggested appropriate types of end-products that can be developed from plastic waste recycling (IS:14534, 2016) [186]. The Waste Framework Directive, revised in 2008, streamlined waste legislation, integrating rules on issues such as the management of dangerous waste and waste oils. The salient details of codal provisions for the management of MSW (plastic waste) set out in some countries are summarized in Table 11.

Table 11. Codes and regulations on MSW/plastic/PET waste in some of the countries.

Country	Act/Regulation/Policies	Salient Details	References
Australia	National Waste Policy-2009	The policy aims to: (a) Ensure that waste treatment, disposal, recovery, and re-use are undertaken in a safe, scientific, and environmentally sound manner (b) Avoid the generation of waste, reduce the amount of waste (including hazardous waste) (c) Contribute to a reduction in greenhouse gas emissions, energy conservation and production, water efficiency, and the productivity of the land (d) Manage waste as a resource (e) Plastics are included in the list of hazardous wastes, and hence unique treatment methods are advised for the same	[187]
China	Waste Management in China: Issues and Recommendations—Urban Development Working Papers East Asia Infrastructure Department World Bank—Working Paper No. 9—May 2005	(a) Recommends aggressively pursuing a waste minimization program making it a key priority area in the management of solid waste (b) Advocates the 4R philosophy, i.e., waste reduction, reuse, recycling, and recovery, with waste reduction (c) Recommends improvements in the waste recycling industry with more professionalization, improved product standards, market development, and better operating standards (d) Recognizes the needs for additional landfills to cater to growing quantities of MSW and improve their operating conditions	[188]
England	Environmental protection, England and Wales—The Waste (England and Wales) Regulations, No. 288, 2011	(a) Advocates a Waste Prevention Programme to reduce the generation of waste	[189]
India	(1) G.S.R. 320 (E) [18-03-2016]: Plastic Waste Management Rules 2016 (2) S.O. 1357(E) [08-04-2016]: Solid Waste Management Rules, 2016	(a) Stipulates individual responsibilities to all government bodies (central and state), municipal bodies, gram panchayat, as well as every waste generator, manufacturer, importer, retailer, producer, and street vendor, in a bid to control the menace of plastic waste (b) The rules prohibit the use of carrying bags (made of virgin plastic or recycled plastic) less than 50-micron thickness to discourage retailers from giving away carry bags (the higher cost of higher-thickness carry bags will deter the retailers from doing so)	[190]

Table 11. *Cont.*

Country	Act/Regulation/Policies	Salient Details	References
Japan	Waste Management and Public Cleansing Law— Law No. 137 of 1970 (amended last in 2001)	(a) Plastic waste is categorized under industrial waste (b) Encourages individuals to set up (plastic) recycling plants (c) Municipal governments are in charge of disposing of urban waste, and the National Government provides funds to them for the implementation of the same under the law	[191]
New Zealand	Waste Management Policy—First formulated in 1995	(a) Adopted the "Waste Generator Pays" approach and encouraged the use of a Waste Management Hierarchy	[192,193]
	Waste minimization act, 2008	(a) The Act aims to reduce the environmental harm of waste and provide economic, social, and cultural benefits for New Zealand (b) Based on the above act, Auckland City formulated its own "Auckland Waste Management and Minimization plan", 2012.	
South Korea	Korea Waste Management Law and Waste Disposal Forms—1991	(a) Regulations for reduction in waste products through the implementation of Extended Producer Responsibility (EPR) have been put into force. (b) The Korea Environment & Resources Corporation (ENVICO) was established to serve as a comprehensive waste management organization	[194]
USA	Resource Conservation and Recovery Act (RCRA) 1976, with amendments from time to time.	(a) The principal federal law in the United States governs the disposal of solid and hazardous waste.	[195]
	Code of Federal Regulations—Title 40, Volume 26, Pt. 258)—2012	(a) Stipulates criteria for municipal solid waste landfills. The regulation deals elaborately with different aspects of landfills such as location restrictions, operating criteria, design criteria, groundwater monitoring, and correction	[196]
	Code of Federal Regulations—Title 40, Volume 26, Pt. 243)—2012	(a) Pertains to "Guidelines for the storage and collection of residential, commercial, and institutional solid waste"	[197]
Norway	Pollution Control Act 1981 (amended last on 20 June 2003)	(a) This Act aims to protect the environment against pollution and to reduce pollution, reduce the quantity of waste, and promote better waste management	Pollution Control Act 1981
Finland	Waste Act (646/2011)	(a) This Act aims to prevent the hazard and harm to human health and the environment posed by waste and waste management, to reduce the amount and harmfulness of waste, to promote the sustainable use of natural resources, to ensure functioning waste management, and to prevent littering	[198]
Slovenia	The Rules on Waste Disposal (2002)	(a) Increase the use of recyclable glass packaging (b) Separate collection of plastic packaging, especially beverage packaging (c) Separate collection of biological and green waste and their processing	[199]

The discussion of this paper delves into the findings and insights generated by exploring the current techniques and approaches used for the management of polyethylene terephthalate (PET) plastic waste. The research question, "What are the current techniques and approaches used for the management of PET plastic waste, with a specific focus on mechanical and chemical recycling methods, rules and regulations in different countries, and applications of recycled PET waste?" guided our investigation and analysis.

Our examination of mechanical recycling methods revealed the significance of sorting, cleaning, and reprocessing techniques in recovering PET waste for reuse. We identified the advantages of mechanical recycling, such as its potential to reduce environmental impact, conserve resources, and contribute to a circular economy. However, challenges such as contamination, degradation, and limited recycling capacity were also noted, indicating the need for continuous improvement and innovation in this area.

The exploration of chemical recycling methods, including glycolysis, pyrolysis, and depolymerization, highlighted their potential for use in converting PET waste into valuable raw materials or feedstocks. These methods offer opportunities for closed-loop recycling and the production of high-quality materials, contributing to a more sustainable PET waste management system. Nonetheless, technological advancements, scalability, and cost-effectiveness remain areas for further research and development.

The discussion also assessed the rules and regulations implemented in different countries, underscoring the importance of policy frameworks in shaping PET waste management practices. Variations in regulations across nations were observed, reflecting diverse approaches to addressing PET waste challenges. Sharing best practices, harmonizing standards, and promoting international collaboration are essential for effective global PET waste management.

Furthermore, the applications of recycled PET waste in various fields were explored, highlighting the potential for utilizing these materials in sectors such as textile manufacturing, packaging, and construction. The adoption of recycled PET in these industries can contribute to resource conservation, waste reduction, and the development of sustainable products.

Overall, this discussion emphasizes the importance of an integrated approach to PET waste management, combining mechanical and chemical recycling methods, while considering the regulatory landscape and exploring diverse applications. It underscores the need for continued research, innovation, and collaboration among stakeholders to achieve a more sustainable and efficient PET waste management system on a global scale.

10. Conclusions

This article presents an overview of the current status of plastic production and consumption, and the share of PET in the same. The focus is on plastic waste disposal and management challenges, particularly for single-use PET items. The article highlights the various regulations in place in different countries for the disposal of Municipal Solid Waste (MSW) and plastic waste, and the methods of waste management that are sustainable and unsustainable. The article also reviews the modern methods of waste disposal that are being adopted worldwide and in India, such as mechanical and chemical recycling. Mechanical recycling, which includes washing, grinding, and pelletizing, is in extensive use due to its simplicity, established technical know-how, and lower investment. Although less popular, chemical recycling yields numerous chemical products that can be used in various applications. Thermal–mechanical recycling methods are also employed to generate electrical energy and fuel gas from plastic waste. The article emphasizes the importance of promoting sustainable development by making stringent regulations for dealing with PET and plastic waste. It also underlines the need for industries that produce this waste to take responsibility for its recycling and reuse, as it can be a profitable business. The end products of recycled PET are used in a wide variety of fields, such as cement concrete, the textile industry, the automobile industry, etc. The installation of new PET recycling plants

or the augmentation of the capacity of existing plants is taking place all over the world, and PET recycling is becoming a big industry by itself.

This study has explored and analyzed the current techniques and approaches used for the management of polyethylene terephthalate (PET) plastic waste. We have gained valuable insights into PET waste management practices. The examination of mechanical and chemical recycling methods, along with the discussion of rules and regulations in different countries, and the applications of recycled PET waste, provides a comprehensive understanding of the subject matter. This study emphasizes the need for integrated waste management strategies and sustainable practices to address the growing environmental concerns associated with PET plastic waste. The findings presented in this paper contribute to the existing knowledge in the field, and provide recommendations by which policymakers and waste management stakeholders can develop effective and sustainable PET waste management solutions.

In conclusion, the management and recycling of single-use PET and plastic waste is a complex issue that requires cooperation from governments, industry, and individuals. Through continued research and development, increased collection and sorting efforts, the promotion of the use of recycled materials, and the development of more efficient and cost-effective recycling methods, it is possible to improve the recycling rate and reduce the environmental impact of plastic waste. PET (polyethylene terephthalate) is a widely used packaging material due to its non-reactivity, durability, and shatterproof properties. However, this has led to an increase in PET waste generation, particularly in the form of single-use items. Recycling PET waste into useful products is considered an eco-friendly and sustainable method of waste management.

The current scenario of recycling techniques and management for single-use PET and plastic waste is a mixed one, with challenges such as contamination and a lack of proper infrastructure. However, there have been several efforts to improve the recycling of single-use PET and plastic waste, including the development of new recycling technologies, increasing collection and sorting, promoting the use of recycled materials, and improving awareness and education. Additionally, more efficient and cost-effective methods, such as chemical recycling, bioplastics, and proper recycling infrastructure, are needed to effectively manage and recycle single-use PET and plastic waste. Therefore, cooperation between governments, industry, and individuals is crucial to ensure the sustainable management of PET waste and to promote the use of recycled materials.

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Abbreviations

BRICS—Brazil, Russia, India, China and South Africa; BHET—Bis-2,hydroxy-ethylene terephthalate; CAGR—Compound Annual Growth Rate; CPCB—Central Pollution Control Board; DMT—dimethyl terephthalate; DEG—diethylene glycol; DSEWPC—Department of Sustainability, Environment, Water, Population and Communities; EG—ethylene glycol; EPA—Environmental Protection Agency; FMCG—fast-moving consumer goods; GBI—Global Business Intelligence; HDPE—high-

density polyethylene; kt—kilotons; PS/EPS—polystyrene/expanded polystyrene; MMT—million metric tons; MT—million tons; PET—poly(ethylene terephthalate); NAPCOR—National Association for PET Container Resources; PP—polypropylene; PVC—poly(vinyl chloride); rPET—recycled PET; RCRA—Resource Conservation and Recovery Act; TERI—The Energy Research Institute; TPA—terephthalic acid; TPD—tons per day.

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Sectoral Assessment of the Energy, Water, Waste and Land Nexus in the Sustainability of Agricultural Products in Cameroon

Boris Abeli Pekarou Pemi [1], Donatien Njomo [1], René Tchinda [2], Jean Calvin Seutche [1], Armel Zambou Kenfack [1], Mahamat Hassane Babikir [3] and Venant Sorel Chara-Dackou [1,4,*]

[1] Energy and Environment Laboratory, Department of Physics, Faculty of Science, University of Yaounde I, Yaounde P.O. Box 812, Cameroon; borisabeli@yahoo.fr (B.A.P.P.)
[2] LISIE, University Institute of Technology Fotso Victor of Bandjoun (IUT-FV), University of Dschang, Bandjoun P.O. Box 134, Cameroon
[3] Department of Physics, University of Ndjamena, N'djamena P.O. Box 1117, Chad
[4] Carnot Energy Laboratory (CEL), Department of Physics, Faculty of Science, University of Bangui, Bangui P.O. Box 1450, Central African Republic
* Correspondence: chav7@yahoo.com

Abstract: To ensure sustainable production and consumption in the agricultural sector, it is necessary to assess the contribution of each element of the nexus in the agricultural production chain. The aim of this study is to make a quantitative and qualitative analysis of the contributions of each element of the energy, water, waste and land nexus to agricultural products. A composite method approach combining aspects based on an input–output model and location quotient (LQ) as well as competitive position is adopted. A database of nexus elements over a period from 2009 to 2018 is used for Cameroon, with ten regions considered. The results show proportions of around 0.42% energy, 67.88% water withdrawal, 11.91% harvested area and 97.81% waste for agricultural products. The geolocation of harvested areas shows that the largest portion is in the far north (1,373,829 ha) and the smallest is in Adamawa (224,038 ha). Maximum production is in the central region (4,334,095 tons) and the minimum is in the Adamawa region (915,841 tons). The central, littoral and west regions are more representative of agricultural products. The analysis of the competitive position of agricultural products contributes to a better orientation of national strategies for agricultural sustainability according to the existing potentials.

Keywords: quantitative and qualitative analysis; nexus energy–water–waste–land–agricultural products; sustainability; consumption and production; Cameroon

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1. Introduction

In a world faced with growing environmental challenges such as climate change, natural resource degradation and demographic pressure, sustainable and efficient agricultural production has become a priority. Water-intensive agriculture is the main sector that feeds humanity, consuming around 70% of the total water consumed [1–3], and the demand for water and energy will continue to grow to meet the world's growing need for food [4,5]. A total of 20.2% or 700 million Africans, according to a 2022 survey by the Food and Agriculture Organization (FAO) of the United Nations, are suffering from hunger. Projections made by ref. [6,7] show an increase in demand for food of 50%, water of 30% and energy of 40% by 2030. Despite modernization and technological progress in the agricultural sector, the number of people suffering from hunger remains alarmingly high and according to the FAO (2022) is expected to reach 600 million by 2030. To this end, many countries are importing more and more agricultural products to satisfy the growing demand for food [8]. Both the food and livestock sectors produce large quantities of organic waste, with animals producing around 8000 billion kilograms of manure over the course of their lives [9]. Worldwide, a significant proportion of the 330 km^3 of municipal wastewater

is of food and organic origin [10]. In this respect, it is necessary to consider an inclusive approach between the different elements of the energy, water, food, waste and land nexus rather than looking exclusively at the effects of each [11].

To understand and plan regional development, including in the agricultural production sector, public authorities need a basic economic approach to better appreciate the impact of each sector of activity on the economy [11]. Moreover, national agricultural production is underpinned by local agriculture, which is inextricably linked to water, energy and fertilizer resources [12], hence the importance of paying particular attention to local agricultural irrigation via solar photovoltaic technologies and the use of organic fertilizers. The importance of modeling a viable ecosystem for beings is emphasized in the sustainable development goals (SDGs) 2, 6 and 7. Given the effects of climate change and the scarcity of water resources, it is more appropriate to make use of water-efficient techniques and technologies that can guarantee better yields [12]. Energy is a key element used for irrigation and product transport; it is therefore necessary to adopt renewable energies as a substitute energy source [13]. Some research has examined the elements of the coupled link, such as [14] the water–energy link, [15] water–food link and [16] energy–food nexus.

A number of recent studies have focused on an approach aimed at understanding the connections between water, energy, food (WEF) and associated elements [12]. The understanding of the interconnections in the energy–water–food (EWF) nexus mainly uses the analysis method via the input–output model [17,18], the spatio-temporal evaluation method with emphasis on a logical coupling arrangement [19] or other similar methods. The culmination of these approaches ensures the security and sustainability of WEF and related elements [20,21].

The work of [22] develops the hypothesis of economic base theory, enabling the economy to be classified into essential (basic) and nonessential (nonbasic) sectors. The distinction between core and noncore sectors is important for understanding a region's economy. Basic sectors are often considered the primary engines of economic growth, as they create jobs, generate income and stimulate other economic activities, while nonbasic sectors provide services and intermediate products needed by the economy as a whole that are mainly used locally [23]. This approach is developed in this work with the aim of classifying basic and nonbasic sectors for each production area. Assessing the basic/nonbasic sector in a local area will enable the government to better understand, target and spend its budget [11].

There are four analysis approaches in the literature: the location quotient (LQ), the assumptions method, the location quotient and the minimum requirements method [22]. The work of [24] developed the LQ as a tool that can be applied to position sectors as basic or nonbasic through a comparison of the sector's potential at the local level with its potential at the regional level. Several sectors have been the subject of the LQ pproach, used in the occurrence of agriculture [25]; the trade sector [26]; industrial concentration [27]; carbon emissions [28]; economic development and interaction [24,29]; road project development [30], the maritime sector [31]; and determining strategies for the water, energy and food sectors in local economic development [11], among others.

Research on the energy–water–food nexus and associated elements is fraught with many questions and criticisms, including regarding the lack of precision of the QL method, which, despite its simplicity and analytical strengths, is frequently used [11,32].

The LQ approach also has positive aspects such as its speed, low cost [33] and absence of primary data in interregional trade [34]. In addition, to analyze the gross domestic product (GDPR), refs. [35,36] made use of the dynamic location quotient (DLQ) in combination with the static location quotient (SLQ). Very few works adopt the energy–water–waste–land (EWWaL) nexus approach for the sustainability of agricultural production.

The main objective of this study is to quantitatively and qualitatively assess the contribution of the energy, water, waste and land sectors to agricultural products through the energy–agricultural products, water–agricultural products, waste–agricultural products and land–agricultural products nexus in each of Cameroon's ten regions. The input–output

method combined with the LQ and competitive cluster graph techniques analyzing the regional production data from the year 2009 to 2018 are used. The proportional contributions of each nexus element to the agricultural sector are determined. The various methods were used to estimate the harvested areas by region, the agricultural production by region and the competitive positions of agricultural products (commodities and non-commodities). This study provides an overview of how energy, water, waste and land resources are linked to agricultural products within a sustainable approach to agriculture. The main contributions of this study are as follows:

- The proportions of the contributions of each network element in the EWWaL chain to agricultural production are determined;
- The geolocation and scale of variation in the harvested areas and total regional production;
- The determination of the zones suitable for each crop in each given region;
- The competitive position of the main products on average by region.

Following the introduction section, Section 2 describes the methodology applied in this research, while Section 3 concerns the presentation of the data. Section 4 presents the nexus indicators (E–W–Wa–L) for agriculture and competitive positioning. Section 5 presents the results and discussion, then the conclusion is in Section 6.

2. Method

This research is organized according to a mixed method combining aspects based on quantitative and qualitative approaches. The following Sections 2.1 and 2.2 summarize the steps and methods employed in this study.

2.1. Quantitative Approach Using the Input–Output Model

The methodology used in this section is an input–output model method for quantitatively assessing the interactions of the energy, water, waste and land (EWWaL) nexus in agricultural production. Adopting this approach, the quantitative equilibrium equation is the modified model equation of Ref. [18]:

$$a_i + y = x \tag{1}$$

a_i represents quantities of intersectoral use, quantity of final demand and x the quantity of resources produced. The vector of total product quantities (x) are nexus by a matrix of intersectoral intensity coefficients (K).

To complete the quantitative resource balance, the interleaved nexus of the E–W–Wa–L for agricultural products is shown in Figure 1.

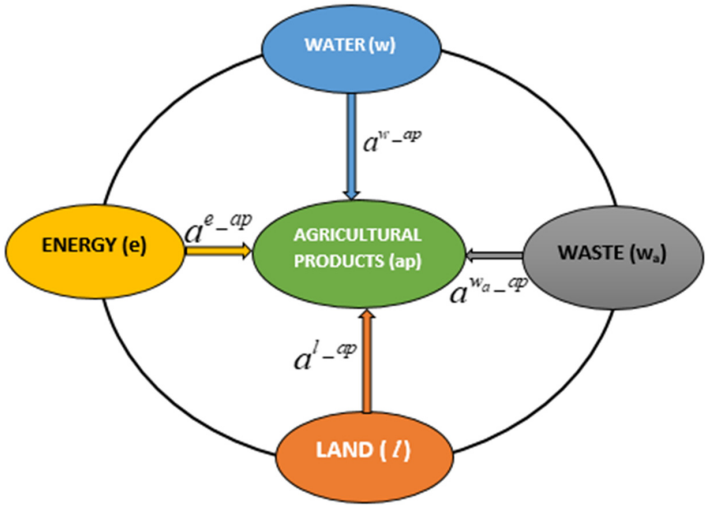


Figure 1. Elements of the energy–water–waste–land nexus for agricultural production.

Where $a_{ij}^{e_ap}$ is the consumption of the *i*th energy resource in the *j*th agricultural products. $a_{ij}^{w_ap}$ is the consumption of the *i*th water resource in the *j*th agricultural products.

$a_{ij}^{w_a_ap}$ is the consumption of the *i*th waste resource in the *j*th agricultural products.

$a_{ij}^{l_ap}$ is the use of the *i*th agricultural area in the *j*th agricultural products. We have

$$\sum_{\mathrm{j}}^{t} a_{ij}^{e_ap} + y_i^{ap} = x_i^{ap} (i = 1, 2, 3, ..., r) \tag{2}$$

$$\sum_{\mathrm{j}}^{t} a_{ij}^{w_ap} + y_i^{ap} = x_i^{ap} (i = 1, 2, 3, ..., s) \tag{3}$$

$$\sum_{\mathrm{j}}^{t} a_{ij}^{w_a_ap} y_i^{ap} = x_i^{ap} (i = 1, 2, 3, ..., u) \tag{4}$$

$$\sum_{\mathrm{j}}^{t} a_{ij}^{l_ap} + y_i^{ap} = x_i^{ap} (i = 1, 2, 3, ..., v) \tag{5}$$

where r, s, u, v and t are, respectively, the number of resources in energy, water, waste, land and agricultural products. The link intensity coefficients in the E–W–Wa–L nexus are governed by the intersectoral link elements $k_{ij} = \frac{a_{ij}}{x_j}$ so

$$k_{ij}^{e_ap} = \frac{a_{ij}^{e_ap}}{x_j^{ap}} \Leftrightarrow a_{ij}^{e_ap} = k_{ij}^{e_ap} x_j^{ap} \tag{6}$$

$$k_{ij}^{w_ap} = \frac{a_{ij}^{w_ap}}{x_j^{ap}} \Leftrightarrow a_{ij}^{w_ap} = k_{ij}^{w_ap} x_j^{ap} \tag{7}$$

$$k_{ij}^{w_a_ap} = \frac{a_{ij}^{w_a_ap}}{x_j^{ap}} \Leftrightarrow a_{ij}^{w_a_ap} = k_{ij}^{w_a_ap} x_j^{ap} \tag{8}$$

$$k_{ij}^{l_ap} = \frac{a_{ij}^{l_ap}}{x_j^{ap}} \Leftrightarrow a_{ij}^{l_ap} = k_{ij}^{l_ap} x_j^{ap} \tag{9}$$

Equations (2)–(5) then become

$$\sum_{\mathrm{j}}^{t} k_{ij}^{e_ap} x_j^{ap} + y_i^{ap} = x_j^{ap} (i = 1, 2, 3, ..., r) \tag{10}$$

$$\sum_{\mathrm{j}}^{t} k_{ij}^{w_ap} x_j^{ap} + y_i^{ap} = x_j^{ap} (i = 1, 2, 3, ..., s) \tag{11}$$

$$\sum_{\mathrm{j}}^{t} k_{ij}^{w_a_ap} x_j^{ap} + y_i^{ap} = x_j^{ap} (i = 1, 2, 3, ..., u) \tag{12}$$

$$\sum_{\mathrm{j}}^{t} k_{ij}^{l_ap} x_j^{ap} + y_i^{ap} = x_j^{ap} (i = 1, 2, 3, ..., v) \tag{13}$$

With $K = \sum k_{\mathrm{ij}}$, the Equations (10)–(13) become

$$K^{e_ap} x_j^{ap} + y_i^{ap} = x_j^{ap} (i = 1, 2, 3, ..., r) \tag{14}$$

$$K^{w_ap}x_j^{ap} + y_i^{ap} = x_j^{ap}(i = 1, 2, 3, ..., s) \quad (15)$$

$$K^{w_a_ap}x_j^{ap} + y_i^{ap} = x_j^{ap}(i = 1, 2, 3, ..., u) \quad (16)$$

$$K^{l_ap}x_j^{ap} + y_i^{ap} = x_j^{ap}(i = 1, 2, 3, ..., v) \quad (17)$$

Equations (14)–(17) take the form $KX^{ap} + Y^{ap} = X^{ap}$ to obtain Equation (18), where K denotes the technology matrix of the E–W–Wa–L nexus.

Finally, we have

$$\begin{pmatrix} K^{e_ap} & 0 & 0 & 0 \\ 0 & K^{w_ap} & 0 & 0 \\ 0 & 0 & K^{w_a_ap} & 0 \\ 0 & 0 & 0 & K^{l_ap} \end{pmatrix} \begin{pmatrix} x^{ap} & 0 & 0 & 0 \\ 0 & x^{ap} & 0 & 0 \\ 0 & 0 & x^{ap} & 0 \\ 0 & 0 & 0 & x^{ap} \end{pmatrix} + \begin{pmatrix} y^{ap} & 0 & 0 & 0 \\ 0 & y^{ap} & 0 & 0 \\ 0 & 0 & y^{ap} & 0 \\ 0 & 0 & 0 & y^{ap} \end{pmatrix} = \begin{pmatrix} x^{ap} & 0 & 0 & 0 \\ 0 & x^{ap} & 0 & 0 \\ 0 & 0 & x^{ap} & 0 \\ 0 & 0 & 0 & x^{ap} \end{pmatrix} \quad (18)$$

$$\begin{pmatrix} 1 - K^{e_ap} & 0 & 0 & 0 \\ 0 & 1 - K^{w_ap} & 0 & 0 \\ 0 & 0 & 1 - K^{w_a_ap} & 0 \\ 0 & 0 & 0 & 1 - K^{l_ap} \end{pmatrix} \begin{pmatrix} x^{ap} & 0 & 0 & 0 \\ 0 & x^{ap} & 0 & 0 \\ 0 & 0 & x^{ap} & 0 \\ 0 & 0 & 0 & x^{ap} \end{pmatrix} = \begin{pmatrix} y^{ap} & 0 & 0 & 0 \\ 0 & y^{ap} & 0 & 0 \\ 0 & 0 & y^{ap} & 0 \\ 0 & 0 & 0 & y^{ap} \end{pmatrix} \quad (19)$$

$$X^{ap} = (I_4 - K)^{-1}Y^{ap} \Rightarrow X^{ap} = LY^{ap} \quad (20)$$

2.2. Qualitative Approach Using Location Quotient and Competitive Position

Ref. [32] defined the LQ as a basic analytical tool for obtaining a coefficient or simple expression of the degree of representation of a particular industry in a given study region. This method is applied in this work to analyze the position of agricultural products in different regions with the same variable at the upper regional level to understand local potential on basic sectors. It is determined from Equation (21).

$$LQ = \frac{w_i / \sum_{i=1}^{j} w_i}{W_i / \sum_{i=1}^{j} W_i} \quad (21)$$

where LQ is the value of the location quotient, represents production of product i in the region j and $\sum_{i=1}^{j} w_i$ is total production in the region j, W_i is the production of product i at national level, while $\sum_{i=1}^{j} W_i$ indicates total production at national level. If the value of LQ for a given production sector is greater than or equal to 1 $(LQ \geq 1)$, it can be classified as a commodity, whereas if the value of LQ is below 1 $(LQ \prec 1)$, it can be classified as a non-basic product. In addition, the value of the production growth rate (P) is obtained by subtracting the value of the production level of product i in the selected year j. (LQ_{ij}) is the value of the production level of product i in the initial year (LQ_{i0}), divided by the value of (LQ_{i0}), then multiplied by 100 (Equation (22)).

$$P = \left(\frac{LQ_{ij} - LQ_{i0}}{LQ_{i0}} \right) \times 100 \quad (22)$$

If the value of P is positive and greater than 10% or 0.1, it reflects that product i is growing and the cluster's level of advantage in the region is increasing. On the other hand, if the value of P is negative and less than -10% or -0.1, this means that growth is declining and the cluster's advantage is decreasing. Furthermore, if the shift is between $+/-10\%$ or $+/-0.1$ this can be considered a very small change.

3. Data Presentation

The data analyzed in this manuscript come from a variety of sources. In the energy demand and production sector, the data are taken from the International Energy Agency [37] database and Cameroon-Electricity Consumption [38], representing the total energy production in Cameroon. The data on agricultural products (production, production demand, irrigated area, water, agricultural waste, energy use in the agricultural sector, manure applied to soils) are taken from the FAO-AQUASTAT database [39], AQUASTAT [40,41], and from ref. [41]. The waste considered is that from agriculture (potatoes, wheat, dried beans, soya beans, rice, corn, millet, sorghum) and livestock (breeding animals, chickens, layers, sheep, horses, goats, cattle, dairy cows, donkeys). The water considered is that taken from underground sources. The energy used in agriculture in this paper is $a_1^{e_ap}$(diesel fuel), $a_2^{e_ap}$(automotive gasoline), $a_3^{e_ap}$ (liquefied natural gas), $a_4^{e_ap}$ (fuel oil), $a_5^{e_ap}$ (carbon), $a_6^{e_ap}$ (electricity). The agricultural products include rice, corn, millet, potatoes, sweet potatoes, cassava, macabo/taro, yams, beans, soy, groundnuts, sesame, onions, okra, peppers, plantains, sweet bananas, cowpeas, pineapples, tomatoes, Bambara, cucumbers, palm oil and watermelons.

4. Link Indicators (EWWaL) for Agriculture and Competitive Positioning

- The use of energy, water, waste and the harvested area in the *j*th agricultural products:

$$a_j^{e_ap} = \sum_i^r a_{ij}^{e_ap}(tep);\ a_j^{w_ap} = \sum_i^r a_{ij}^{w_ap}(\mathrm{Mm}^3); \tag{23}$$

$$a_j^{w_a_ap} = \sum_i^u a_{ij}^{w_a_ap}(t);\ a_j^{l_ap} = \sum_i^v a_{ij}^{l_ap}(\mathrm{ha}). \tag{24}$$

- The consumption of energy, water, waste and the harvested area linked to the agricultural products:

$$a^{e_ap} = \sum_j^t \sum_i^r a_{ij}^{e_ap}(tep);\ a^{w_ap} = \sum_j^t \sum_i^s a_{ij}^{w_ap}(\mathrm{Mm}^3); \tag{25}$$

$$a^{w_a_ap} = \sum_j^t \sum_i^u a_{ij}^{w_a_ap}(kt)\ ;\ a^{l_ap} = \sum_j^t \sum_i^v a_{ij}^{l_ap}(\mathrm{ha}). \tag{26}$$

- The intensity of the use of energy, water, waste and the harvested area related to the agricultural products:

$$k_j^{e_ap} = \frac{a^{e_ap}}{x_j^{ap}}(toe/t);\ k_j^{l_ap} = \frac{a^{l_ap}}{x_j^{ap}}(\mathrm{ha/t}); \tag{27}$$

$$k_j^{w_a_ap} = \frac{a^{w_a_ap}}{x_j^{ap}}(kt/t)\ \ k_j^{l_ap} = \frac{a^{l_ap}}{x_j^{ap}}(\mathrm{ha/t}). \tag{28}$$

- The proportion of energy, water, waste and land consumption linked to agricultural products in relation to the total energy, water, waste and land consumption in (%).
- The location quotient and competitive position of main products by region.

5. Results and Discussion

5.1. Energy Nexus Indicator for Agricultural Production

Energy plays an essential role in agricultural production. Table 1 shows the quantification of the different forms of energy used in the agricultural production sector over the period 2009 to 2020. During this period, fuel oil emerged as the most widely used form of energy, followed by diesel, liquefied natural gas, electricity, a constant value use of coal and a very low value use. There are several reasons why the agricultural sector in Cameroon

uses more fossil energy sources, not least the availability of fossil energy sources. Fossil fuels such as oil and natural gas have long been available and widely used in the country. They are easily accessible and more affordable in terms of costs for farmers. Furthermore, the infrastructure needed to use clean energies such as solar or wind power can be costly to set up. In Cameroon, there is still a lack of suitable infrastructure to enable a transition to clean energies in the agricultural sector, which hampers their use. The lack of subsidies and incentives to encourage the use of clean energy in the agricultural sector may also be a factor. However, it is important to note that the transition to clean energy sources in the agricultural sector is increasingly being encouraged in many countries, including Cameroon, as Ref. [42] has highlighted. Initiatives and programs to promote the use of renewable energies and sensitize farmers to their benefits would be necessary, as Ref. [43] highlights their ongoing development. This is to promote agricultural sustainability.

Table 1. Energy consumption by agricultural production in tons of oil equivalent.

Energy for Agriculture \ Support	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
$a_1^{e_ap}$	8645.3	9230.12	9627.97	9517.5	9852.24	10,549	9081.52	9350.09	9678.84	9969.61	9853.6	9853.64
$a_2^{e_ap}$	4843.67	4746.52	4940.82	5162.88	5440.45	5759.7	6953.24	6967.11	5731.91	5190.64	5076.8	5076.83
$a_3^{e_ap}$	6642.13	7096.025	7797.55	7796.86	7919.88	8657.6	8548.26	8637.46	7038.96	6435.84	5991.5	5991.49
$a_4^{e_ap}$	11,849.49	12,451.79	12,786.8	12,999.3	13,497.9	15,864	5816.58	6112.2	6940.44	7774.19	6156.3	6156.273
$a_5^{e_ap}$	54.04	54.04	54.048	54.04	54.043	54.04	54.04	54.04	54.04	54.04	54.04	54.04
$a_6^{e_ap}$	4371.51	5142.96	5742.97	6000.12	6257.26	6685.8	4971.52	4457.23	5057.24	5400.1	5143	5142.96
a^{e_ap}	36,406.1	38,721.5	40,950.2	41,530.7	43,021.7	47,570.1	35,578.1	34,501.4	34,501.4	34,824.4	32,275.2	32,275.2

Figure 2 The share of different forms of energy used in the agricultural production sector over four consecutive years is shown. It can be seen that for the different forms of energy as a whole, there is very little variation in usage and this fluctuates around 1%.

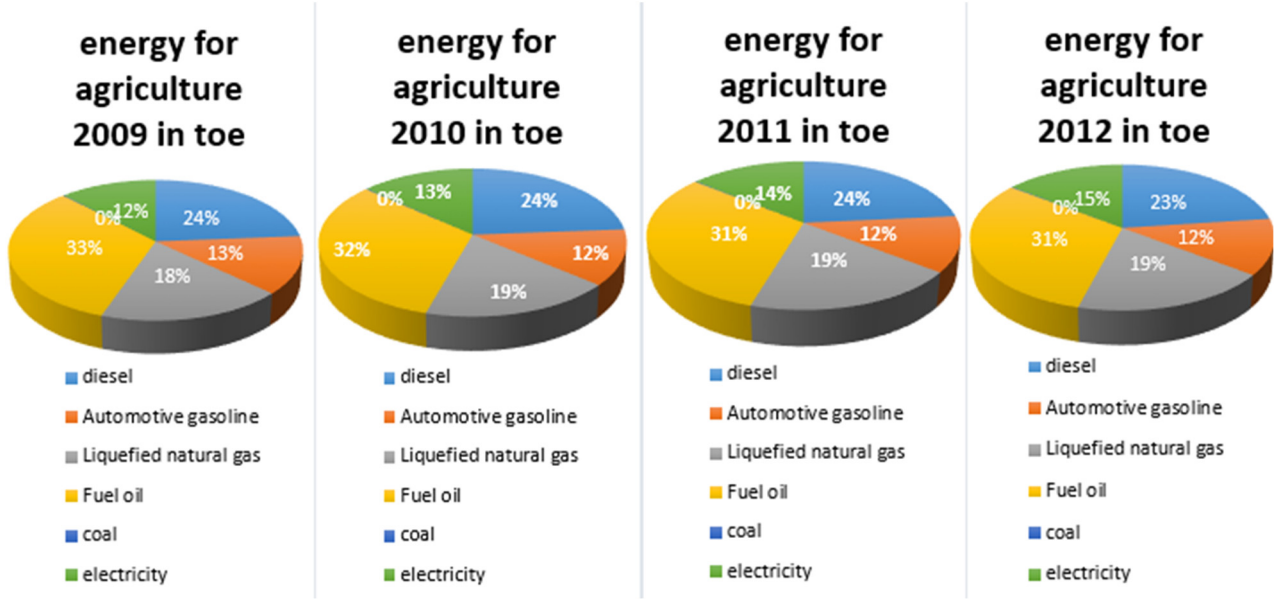


Figure 2. Proportion of energy consumption in the agricultural production sector from 2009 to 2012.

Figure 3 shows an increase of 4% in the use of motor gasoline between 2014 and 2015, which most probably signifies an expansion of developed agricultural land, the modernization of the sector in terms of agricultural equipment (new farm machinery and mechanized harvesting) and an increase in working hours. There has also been a drop in the use of fuel oil, which fell by more than 50% between 2014 and 2015, and an increase in the share of liquefied natural gas of around 6%. This can be explained by the variety of machine types used and their marginal productivity.

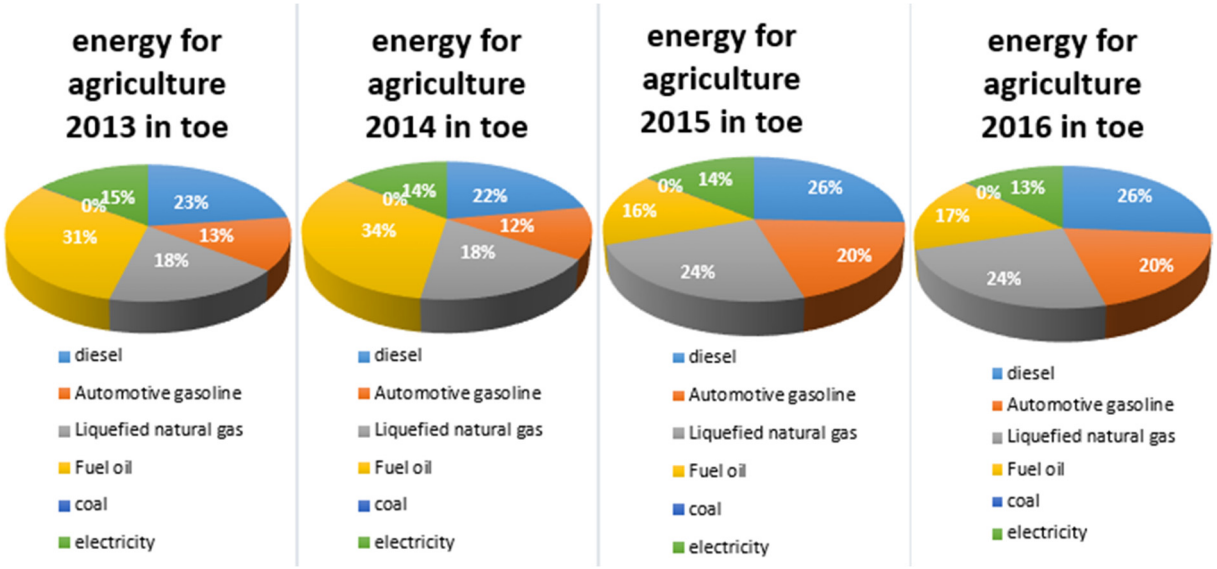


Figure 3. Proportion of energy use in the agricultural production sector from 2013 to 2016.

Table 2 shows the overall increase in production and total agricultural area from 2009 to 2018. An overall increase in production can be observed over this period. As for the agricultural area, a decrease of 6% is observed between 2016 and 2017. In this period (2016 to 2017), Figure 4 shows a 3% drop in motor gasoline and a 4% drop in liquefied gas. However, we cannot specifically conclude that these declines are the cause of the decrease in agricultural land, as the 2017 to 2018 period saw a further decline in motor gasoline (2%) and liquefied gas (2%), while the harvested agricultural land increased by 4.7%.

Table 2. Agricultural production in tons and area in ha.

Year	2009	2010	2011	2013	2014	2015	2016	2017	2018
Total agricultural production (x^{ap})	15,266,818	16,765,766	17,567,744	19,155,918	20,417,861	20,961,495	21,255,814	21,871,448.3	22,342,775
Total area harvested (ha)	5,492,937	5,999,641	6,208,182	6,305,190	6,629,460	7,161,306	7,901,028	7,423,803	7,793,055

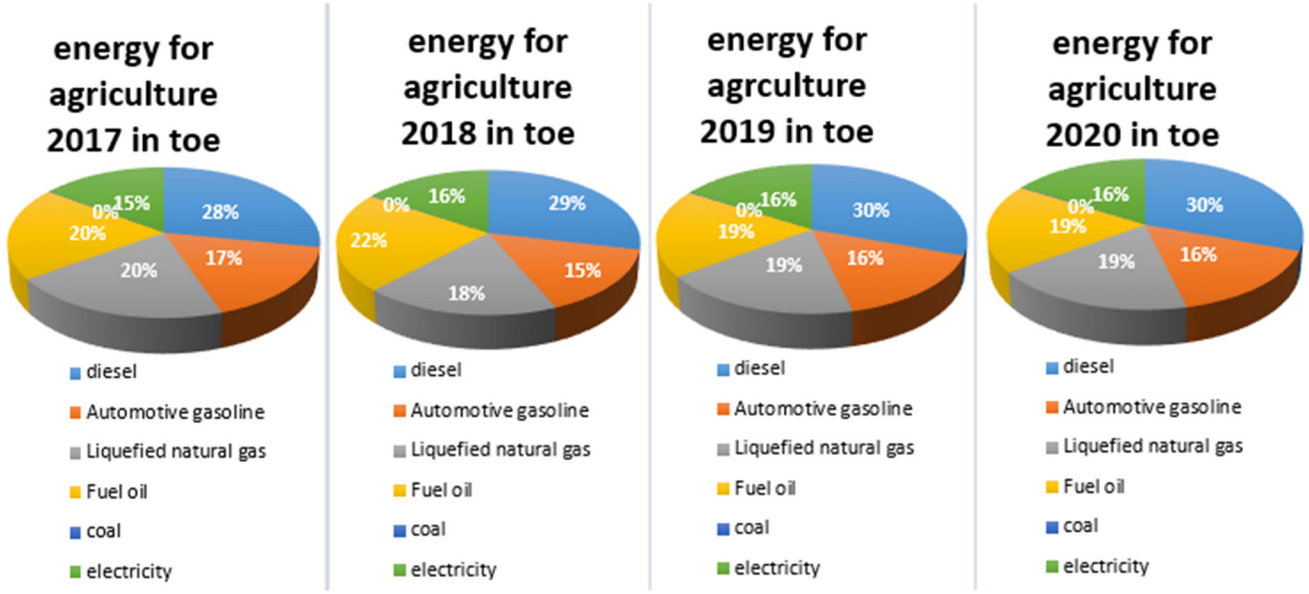


Figure 4. Proportion of energy use in the agricultural production sector from 2017 to 2020.

In conclusion, cultivated farmland is not very dependent on energy availability, but is mostly ploughed using human and animal labor. This conclusion is in line with Ref. [44], which states that draught animals provide 10% of the agricultural energy, with 89% of the remainder provided by human power (farmers' arms). The mechanization of agriculture is likely to increase production, attract young people to farming, and reduce unemployment and the high rural exodus of young people in Africa and Cameroon in particular.

The results in Table 3 show a gradual increase in energy consumption by the agricultural sector between 2009 and 2014, which also reflects the drop in consumption between 2014 and 2018. However, it is important to put these figures into perspective with the corresponding agricultural production over the same period. Agricultural production rose significantly, from 15,266,818 tons in 2009 to 22,342,775.3 tons in 2018—an increase of 46.36% in this decade. It appears that between 2009 and 2018, the average value of the energy share per ton of production was 0.0020 toe/t.

Table 3. Energy intensity for agriculture (in toe/t).

Year	2009	2010	2011	2013	2014	2015	2016	2017	2018
a^{e_ap}	36,406.1	38,721.4	40,950.1	43,021.7	47,570.1	35,425.1	35,578.1	34,501.4	34,824.4
k^{e_ap}	0.002384	0.002309	0.002330	0.002245	0.002329	0.001690	0.001673	0.001577	0.001558

This suggests that, despite a fall in energy consumption, the agricultural sector has managed to increase its production significantly. This is the result of a more efficient and sustainable use of energy, as well as other factors such as the adoption of advanced agricultural technologies.

In conclusion, although energy consumption by the agricultural sector has fallen over a period of time, this has had no significant impact on growth in agricultural production. Figure 5 shows the intensity of energy use in the agricultural sector as a proportion of the total consumption.

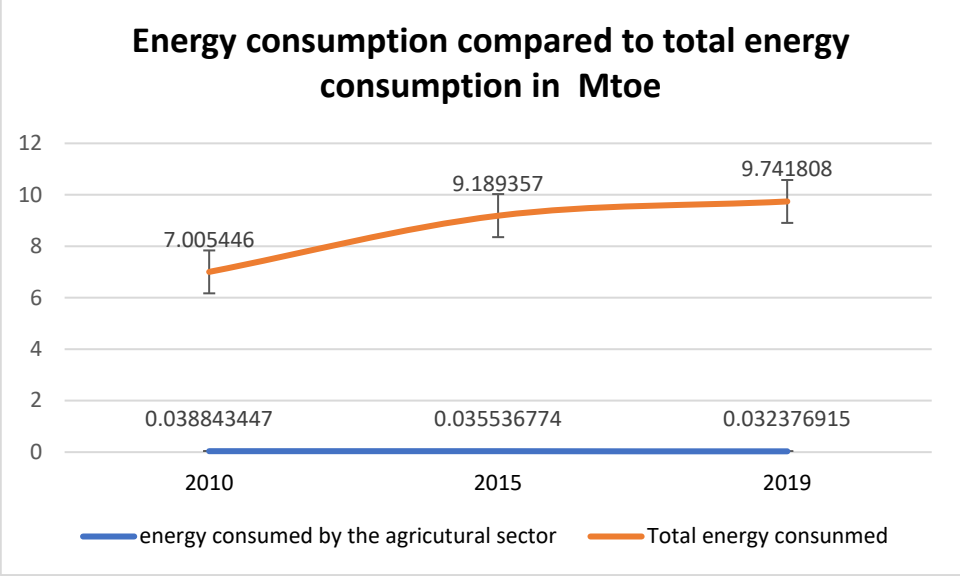


Figure 5. Proportion of energy consumed by agriculture to total energy consumed in toe.

It is interesting to note from Figure 5 that the energy consumption by the agricultural sector as a proportion of the total energy consumption is relatively low and has a downward trend throughout the period studied. Between 2010 and 2015, this consumption falls from 0.55% to 0.38%, then from 0.38% to 0.33% between 2015 and 2019.

These results suggest that the agricultural sector has made progress in energy efficiency over time. The decrease in the energy consumption in 2010 and 2019 can be attributed to

more sustainable farming practices and the adoption of energy-saving technologies. In addition, the security situation and the various crises recorded in the country during this period could have a significant impact on the country's hydrocarbon supply policy. It is important to stress that, in order to draw more accurate conclusions, it would be useful to compare these figures with those of other regions or sectors. This would make it possible to determine whether the energy consumption of agriculture is relatively low compared to other sectors, or whether it is specific to this particular region. In addition, it could be interesting to dig deeper to understand the specific factors that have contributed to the decrease in energy consumption between 2015 and 2020, in order to apply them to other regions or industries. However, further analysis of comparative figures and specific factors is required to draw more robust conclusions and also consider structural measures. From an environmental point of view, the low energy consumption in the agricultural production sector has a positive impact on the environment, as it is heavily dominated by fossil fuel sources (around 85%).

5.2. Water to Agricultural Products Nexus Indicator

Figure 6 shows the water withdrawal in billions of cubic meters for various sectors, including agriculture. The various sectors have managed to optimize their water consumption despite constant water use from 2009 to 2018; their growth is probably linked to investment in more efficient technologies and developing more sustainable practices to reduce their water footprint. This optimization of water use is important to ensure a balanced and sustainable use of water resources, given their scarcity. However, it would also be important to closely monitor the impact of sector growth on the environment, particularly with regard to water quality and the availability of water resources for local communities and ecosystems. Indeed, water quality monitoring is essential to prevent water contamination, protect human health and preserve the environment in the context of agriculture. This enables appropriate measures to be taken to ensure the sustainable management of water resources and preserve the quality of life of the populations concerned. The assumption of rain-fed agriculture is also possible to understand the constant use of water abstraction and increasing agricultural production.

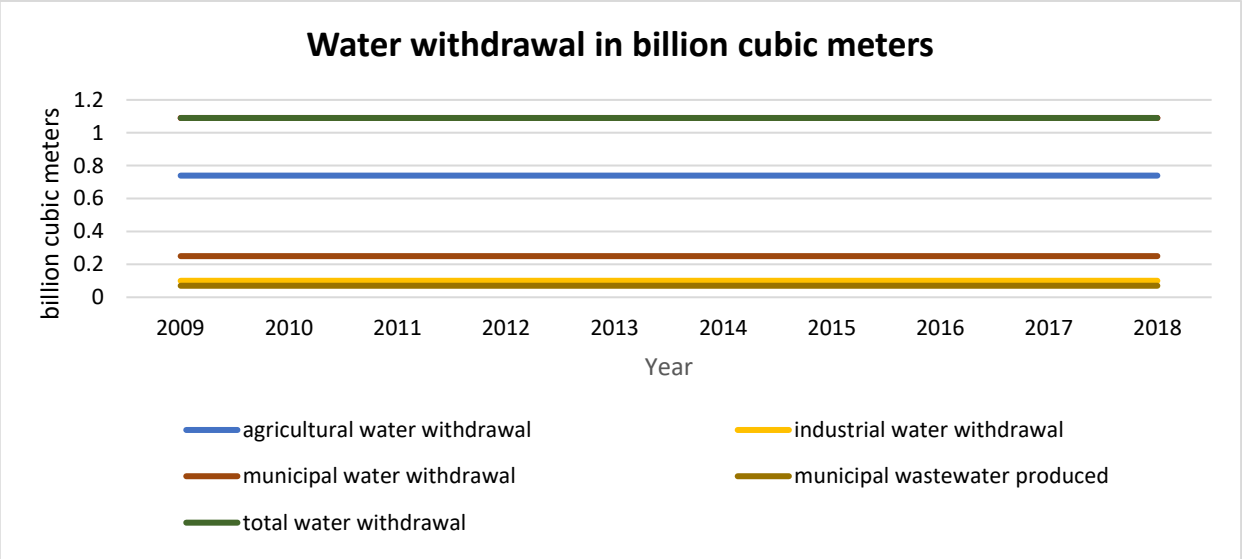


Figure 6. Water withdrawal in billion cubic meters.

Permanently and temporarily irrigated areas, as shown in Figure 7, have remained constant on average from 2009 to 2018. Specifically, temporarily irrigated areas are more dominant than permanently irrigated areas.

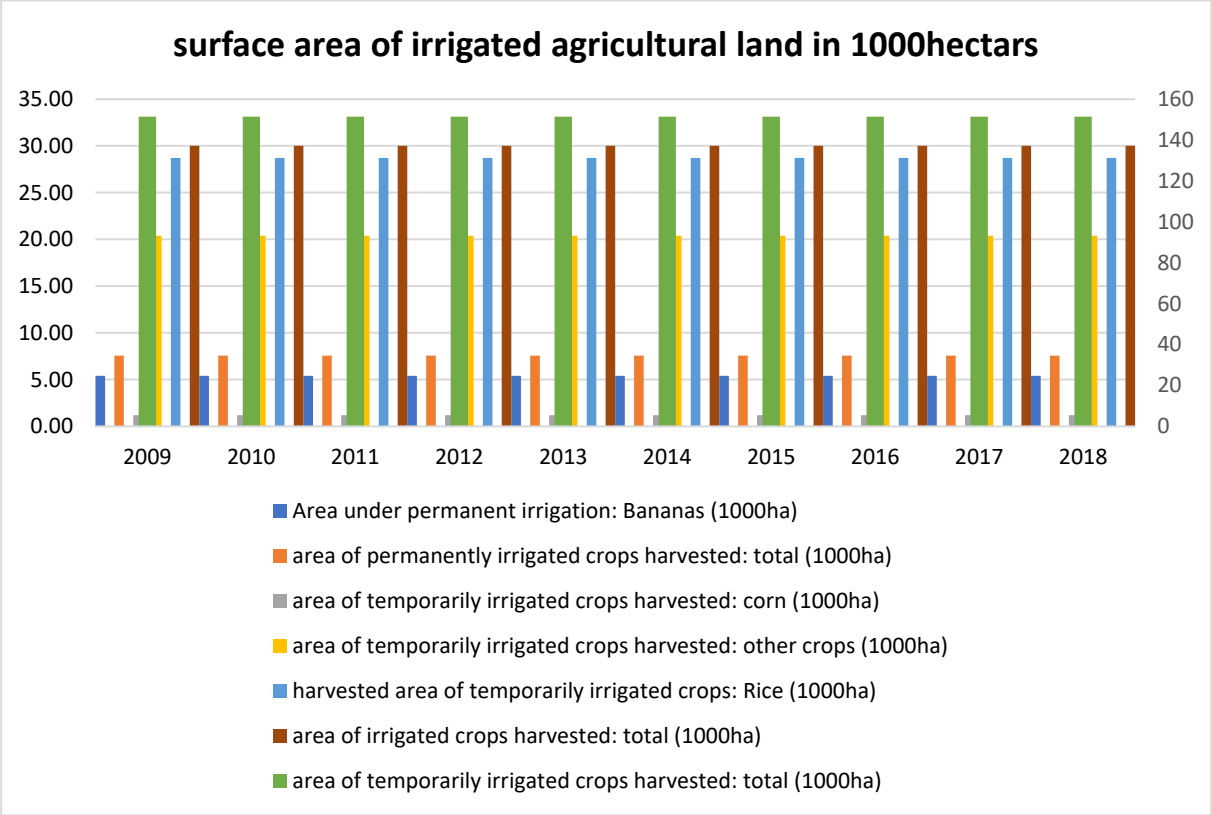


Figure 7. Irrigated land area in 1000 hectares.

Figure 8 shows that the agricultural sector consumes three times more abstracted water than the total municipal water abstracted. However, water abstraction requires energy, and the use of renewable energy sources for agricultural water abstraction offers numerous advantages, both environmentally and economically. This contributes to the sustainability and resilience of the agricultural sector.

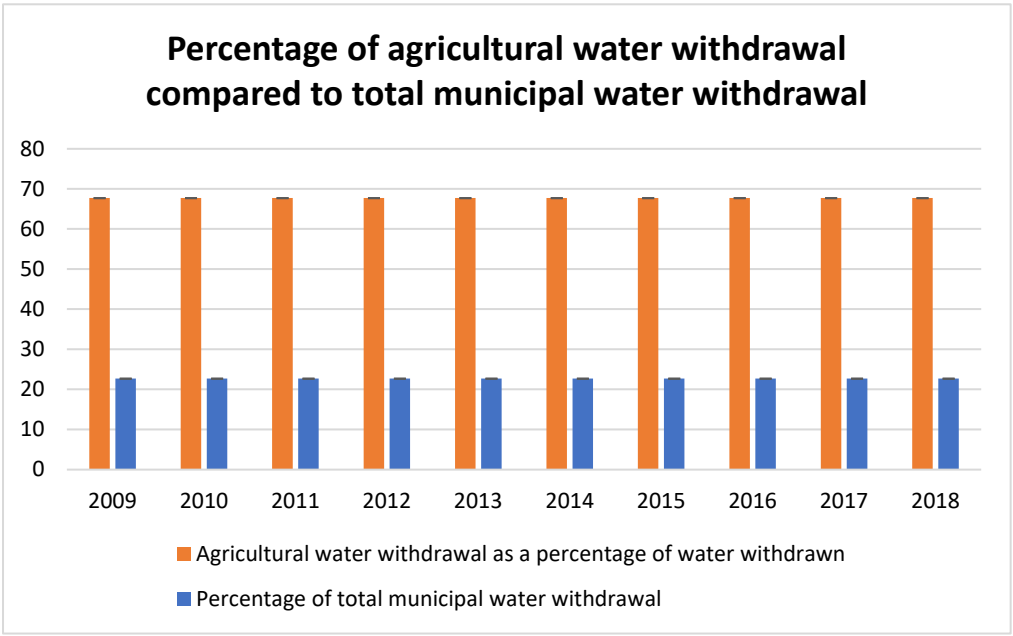


Figure 8. Percentage of water withdrawal.

5.3. Waste Index in the Agriculture Sector

Figure 9 above shows the quantitative application of agricultural and livestock wastes to agricultural land. It is important to note that agricultural residues and wastes can have a significant impact on agricultural production through their various uses to improve soil quality, increase nutrient availability, reduce fertilizer costs, produce energy and contribute to more sustainable and efficient agriculture.

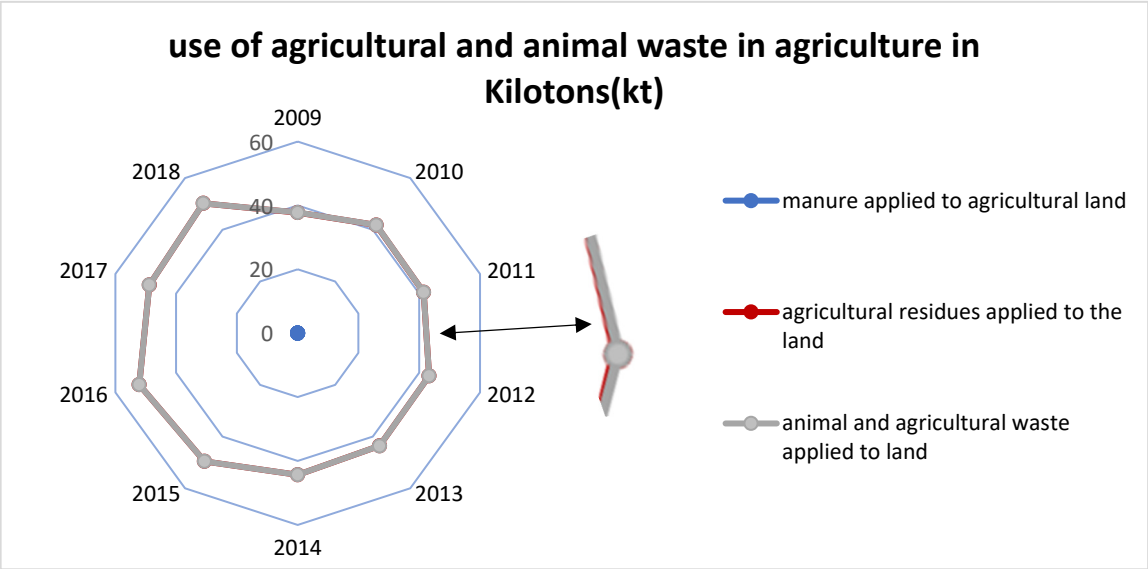


Figure 9. Agricultural and animal waste products, applied to farmland as fertilizer.

5.4. Indicator of the Link between Land and Agricultural Products

Table 4 shows the areas used for crops by region and by year of agricultural production from 2009 to 2018. The overall trend is upward, with a slight drop between 2016 and 2017.

Table 4. Total harvested area by region and by year in hectares from 2009 to 2018.

Region \ Year	2009	2010	2011	2013	2014	2015	2016	2017	2018
Adamawa	232,750	240,656	249,878	252,120	242,204	264,824	274,716	235,376	224,038
East	322,905	328,920	336,516	405,651.8	475,310	426,657	453,573	471,390	495,511
Extreme north	1,220,298	1,276,581	1,371,507	1,157,857	1,271,018	1,470,350	1,664,934	1,408,657	1,523,260
Center	449,188	518,163	560,139	596,910.1	65,7933	716,184	1,008,448	995,837	995,106
Coast	238,595	242,448	259,672	300,544.2	306,602	332,491	316,105	312,497	321,274
North	731,562	834,192	807,114	745,242	557,910	610,054	679,874	541,357	727,347
Northwest	286,843	323,702	324,586	357,767.9	342,239	380,964	387,061	420,130	369,569
West	349,006	393,337	408,397	426,520.1	466,926	508,805	534,484	547,221	590,772
South	198,329	215,441	193,458	239,108.2	236,628	247,209	254,725	277,902	288,668
Southeast	221,939	223,614	255,888	287,234.9	395,678	425,820	385,443	410,245	310,412
total harvested area	4,251,415	4,597,054	4,767,155	4,768,956	4,952,448	5,383,358	5,959,363	5,620,612	5,845,957

Table 5 shows the total agricultural production values by region from 2009 to 2018. Overall, the country's total agricultural production increased throughout the study period. This is due to the policy implemented in this sector.

Table 5. Agricultural production by region and production year in tons from 2009 to 2018.

Region \ Year	2009	2010	2011	2013	2014	2015	2016	2017	2018
Adamawa	601,239	653,456	690,485	701,610.4	812,018.3	837,511.3	875,211.41	957,323.57	915,841.6
East	2,314,422	2,545,175	2,562,955	2,859,342	3,059,880	3,087,826	3,195,323.2	3,312,104.3	3,523,418
Extreme north	1,391,105	1,532,055	1,680,572	1,420,537	2,119,417	1,695,005	1,829,544.6	1,949,470.4	2,088,645
Center	3,332,719	3,770,770	3,935,911	4,361,647	4,352,880	4,862,870	4,807,993	4,770,443	4,811,630
Coast	1,571,230	1,669,606	1,778,089	1,990,227	1,802,874	2,069,895	2,056,517	2,215,026	2,252,271
North	831,766	833,744	849,444	1,154,181	1,113,217	911,454.4	972,090.38	1,132,636.1	1,307,307
Northwest	976,659	971,479	1,004,983	1,322,290	1,141,398	1,223,768	1,236,945	1,306,051	1,299,363
West	1,590,528	1,795,924	1,849,424	1,962,754	2,143,938	2,286,753	2,326,221	2,350,412	2,537,870
South	1,538,096	1,652,719	1,652,080	1,993,770	1,925,872	2,018,704	2,078,278	2,134,095	2,287,873
Southeast	1,119,054	1,340,838	1,563,801	1,389,560	1,946,366	1,967,709	1,877,691	1,743,887	1,318,556
total production	15,266,818	16,765,766	17,567,744	19,155,918	20417,861	20,961,496	21,255,815	21,871,448	22,342,775

5.5. Average Production Yield Per Hectare from 2009 to 2018 by Product and Region

In Figure 10, the cassava yields are highest in the Southwest (79.61 t/ha), Center (30.24 t/ha) and Littoral (18.26 t/ha) regions, while low-yielding products (10.39 t/ha) have the lowest yields of any region in the country. Potatoes are also favored in the Adamawa (26.26 t/ha), West (14.13 t/ha), South (13.96 t/ha), Southwest (13.24 t/ha), Northwest (12.15 t/ha) and Coast (12.37 t/ha) regions. Yam is also one of the crops grown in almost every region of the country, with the central region showing the highest average yield per hectare (47.21 t/ha), followed by Adamawa (13.42 t/ha) and 12.18 t/ha in the Northwest.

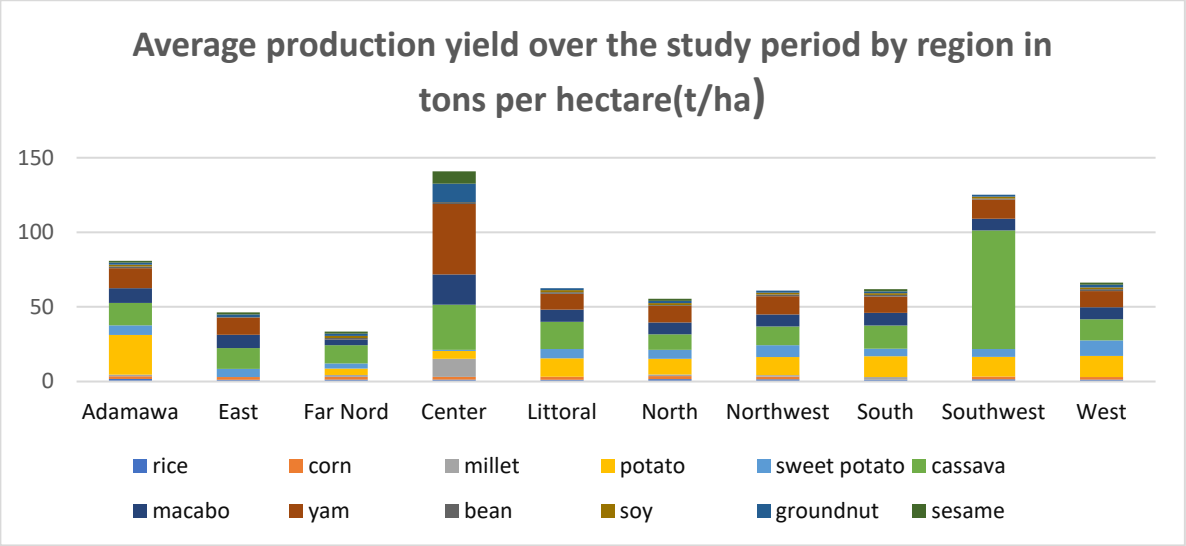


Figure 10. Average production yield by region and product.

Figure 11 shows the average pineapple yields per hectare in the Southwest at 66.01 t/ha, South at 58.3 t/ha, West at 28.09 t/ha, Northwest at 33.28 t/ha, Coast at 26.54 t/ha and East at 26.25 t/ha. Watermelons also showed average yields of 24.09 t/ha in the Southwest, South, West, East, Coast and Northwest regions. Plantain and sweet bananas show good yields in the Central region, at 40.77 t/ha and 36.32 t/ha, respectively, in the South at 13.67 t/ha and 18.52 t/ha, in the Southwest 11.68 t/ha and 19.8 t/ha, and in the Littoral region 13 t/ha and 14 t/ha. An analysis of the agricultural yields per hectare by region in a given locality enables investors and farmers to better plan their production and harvests, produce sufficient quantities of quality food, stimulate the local economy and contribute to sustainable agriculture.

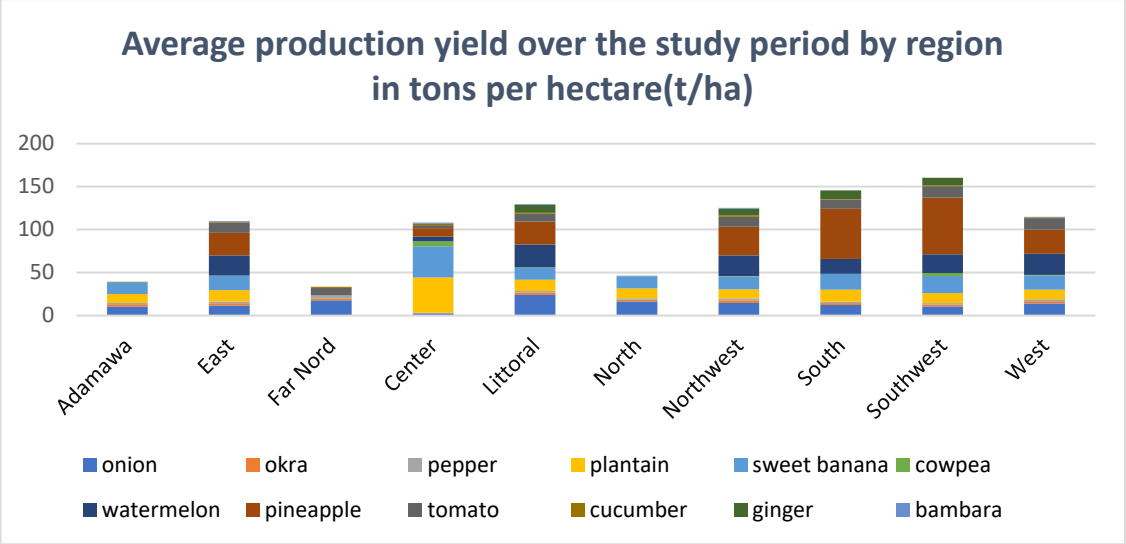


Figure 11. Average yield by region and product.

5.6. Agricultural Production and Harvested Areas by Region and Year

The bubble sizes for the various harvested areas and agricultural products by region and year in this sub-section correspond to the values in Tables 4 and 5, respectively.

Figures 12 and 13 show the respective variations in farmland area and production for three consecutive years (2009 to 2011). Between 2009 and 2011, the overall harvested area increased in almost all regions, with a slight drop of −3.2% in the North and −10% in the South in 2011. Over the same period, production also showed an upward trend, which was significant in some regions and insignificant in others. This is in line with the observations made in Tables 4 and 5. However, there is a mismatch between the harvested area and production. In the Southwest, production increased by 20% and in the North by 0.2%, while the harvested area increased by 0.8% and 14%, respectively, over the same period.

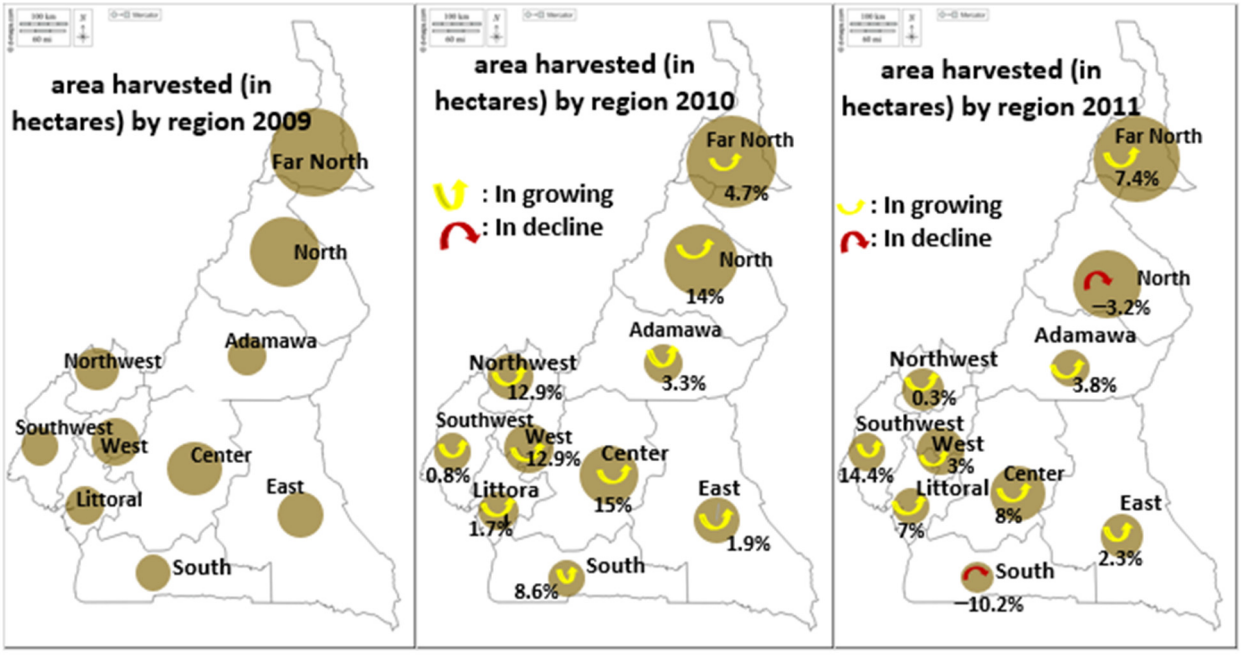


Figure 12. Rate of change in agricultural land area in 2009, 2010, 2011 in hectares (in ha).

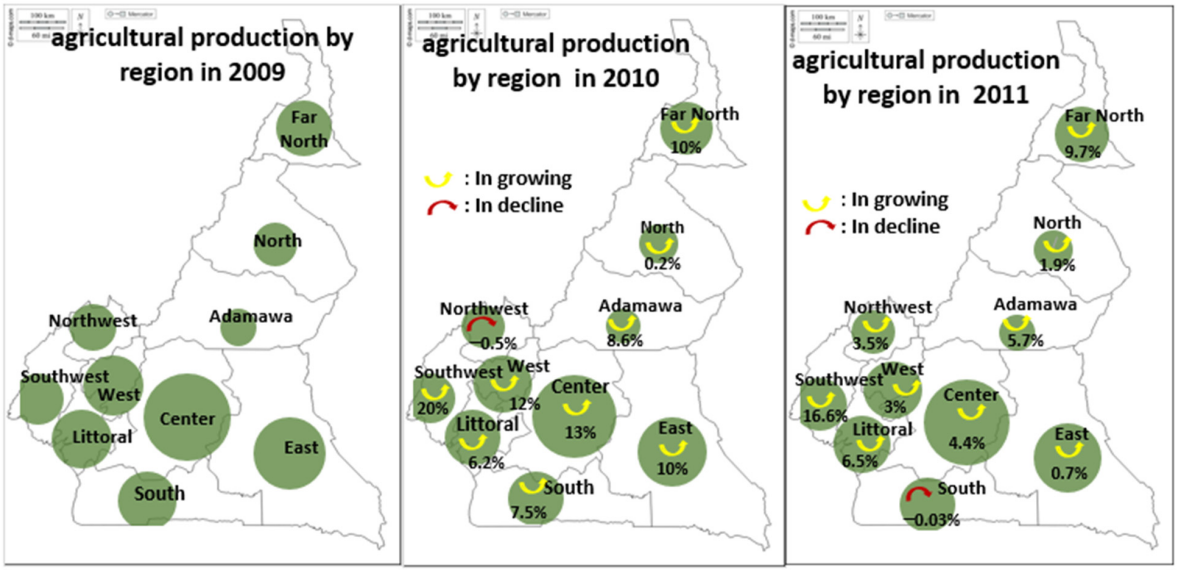


Figure 13. Agricultural production and rate of change agricultural production in years 2009, 2010, 2011 in hectares.

Figures 14 and 15 illustrate the variability of the harvested areas and production over 2013, 2014 and 2015. The proportion of the variation in production is similar in the Far North region (a 15% drop in the harvested area and a drop in production of the same absolute value in 2013) and the Southwest region (a 40% increase in production for a 38% increase in the harvested area in 2014). This is not the case for the North (a −7.7% drop in the harvested area versus a 36% increase in production in 2013), Southwest (a 23.5% increase in the harvested area versus an 11% drop in production in 2013) and Far North (a 10% and 15% increase in the harvested area, respectively, in 2014 and 2015 versus a 49% increase in production in 2014 and a 20% drop in production in 2015) regions. These observations allow us to conclude that production is not solely dependent on the harvested area. An increase in the harvested area does not necessarily guarantee an increase in agricultural production.

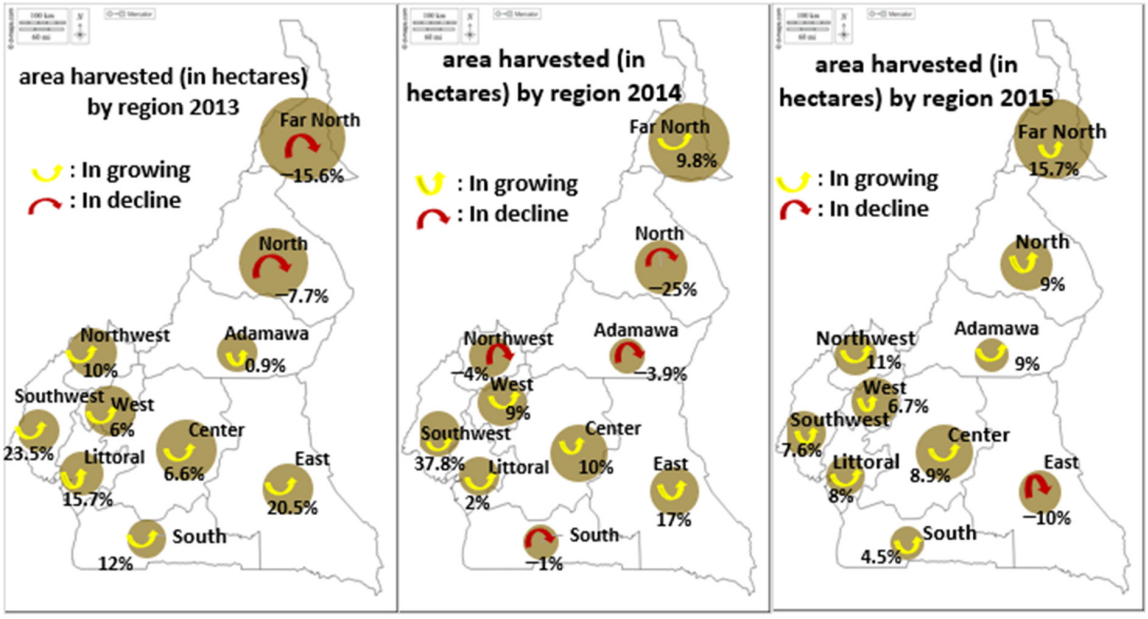


Figure 14. Agricultural area and rate of change in agricultural land area in years 2013, 2014, 2015 in hectares.

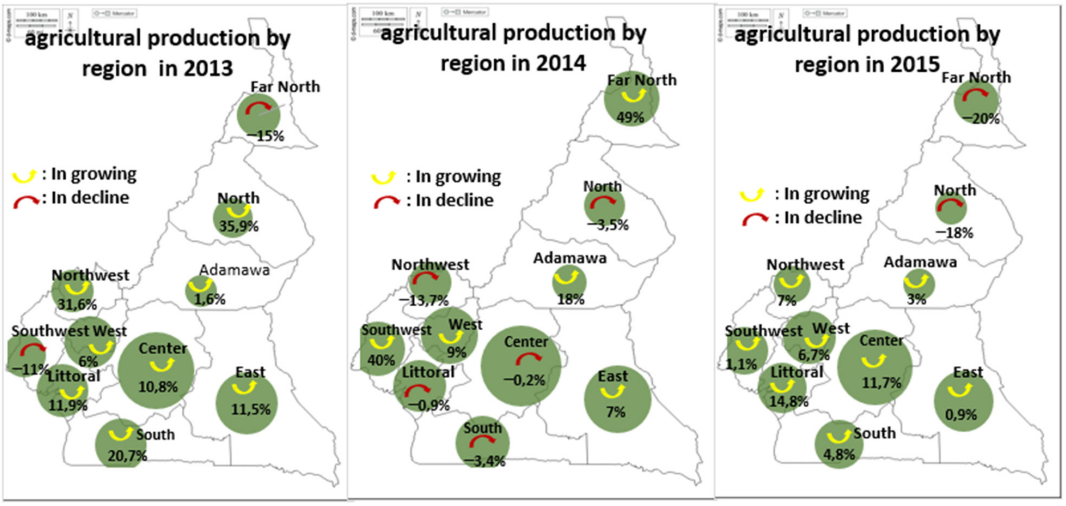


Figure 15. Agricultural production and rate of change in agricultural production in years 2013, 2014, 2015 in hectares.

Figures 16 and 17 show the variations in the harvested area and production for the consecutive years 2016, 2017 and 2018. As in Figures 10–13, there are both consistencies and inconsistencies between the variations in the harvested area and variations in production. There are many factors that can influence the yield of agricultural production. Some of the main factors are weather conditions (climatic conditions, such as rainfall, temperature and sunshine), which can have a major impact on crop growth. Then, there's the soil (soil quality and fertility are essential for good crop growth), farm inputs (the use of fertilizers, pesticides, high-quality seeds and other farm inputs can play a major role in crop yield), crop management (effective crop management, including crop rotation, weed management, disease and pest control and crop planning, can contribute significantly to agricultural production yields), agricultural technologies (the use of modern agricultural technologies such as drones, sensors, remote sensing systems and precision farming can help optimize farming practices and increase yields). These factors often interact in complex ways, and their differentiated impacts on agricultural production yields can vary according to specific regions, crops and farming systems.

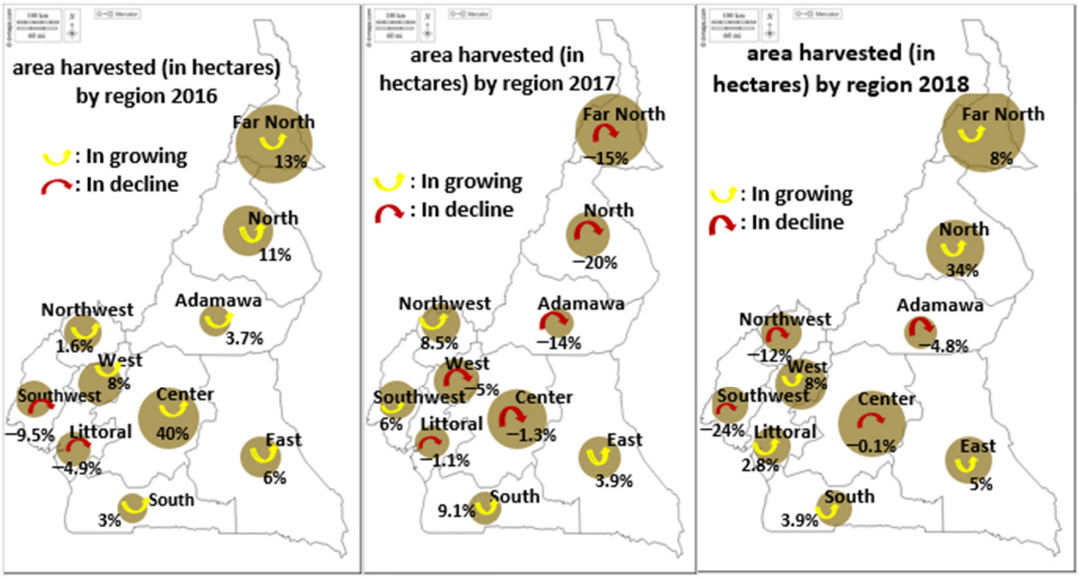


Figure 16. Agricultural area and rate of change in agricultural land area in years 2016, 2017, 2018 in hectares.

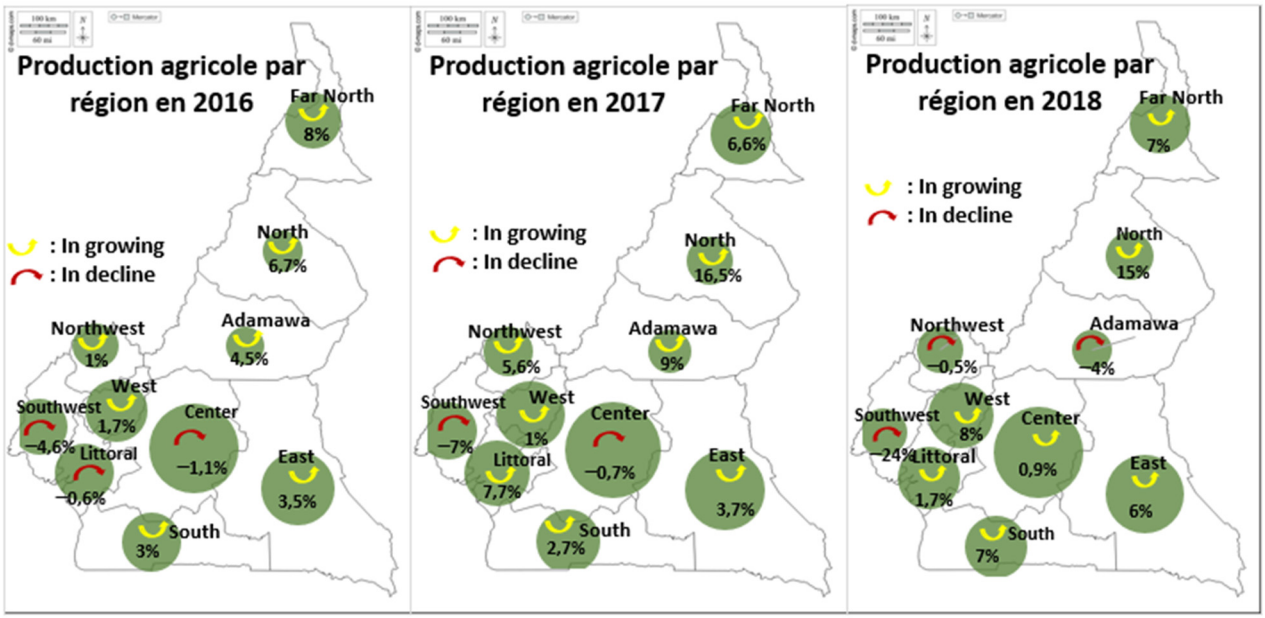


Figure 17. Agricultural production and rate of change in agricultural production in years 2016, 2017, 2018 in hectares.

5.7. Average Competitive Position of Main Products by Region

Figure 18 shows the main products on average in the Adamawa region. It can be seen that tomatoes, corn and yams are considered local staples. However, macabo and taro are non-basic products that are growing rapidly.

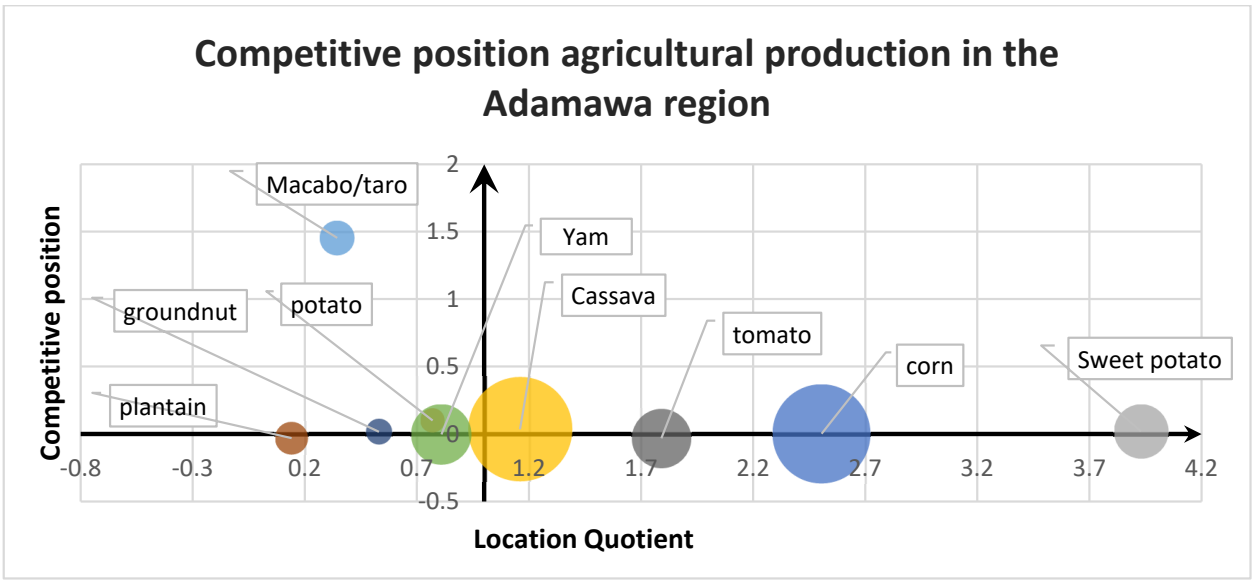


Figure 18. Competitive position of main products on average from 2009 to 2018 in the Adamawa region.

Figure 19 shows the different positions occupied by products in the East region. It shows that groundnuts, taro macabo and yams are the staples in the locality, while sweet potatoes, cucumbers and maize are nonstaples. Bean and palm oil production declined throughout the study period.

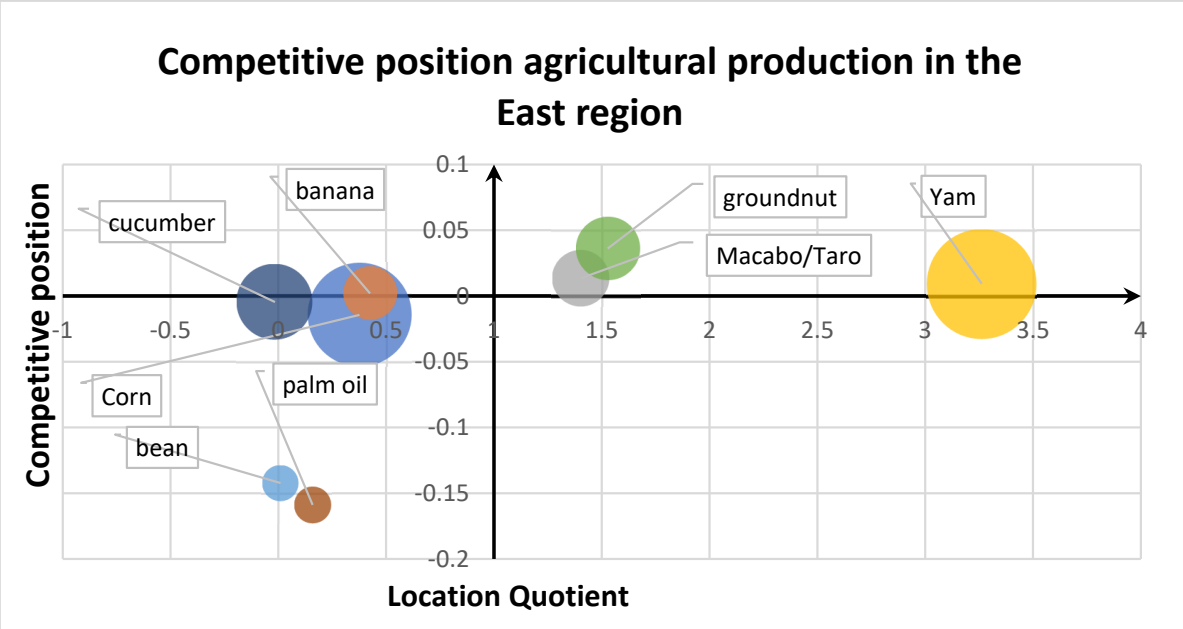


Figure 19. Competitive position of main products on average from 2009 to 2018 in the East region.

In the Far North region, as shown in Figure 20, no single product is the staple, but the main products in this locality are growing, with the exception of beans and millet, which are not showing any significant decline. The Far North of the country is complex due to a number of factors. The region faces challenges such as food insecurity, resource-related conflicts, climate change and land degradation. The region's agricultural support policies and programs need to be further strengthened, and other initiatives to promote the sustainability of farming systems and strengthen the resilience of local populations are strongly recommended.

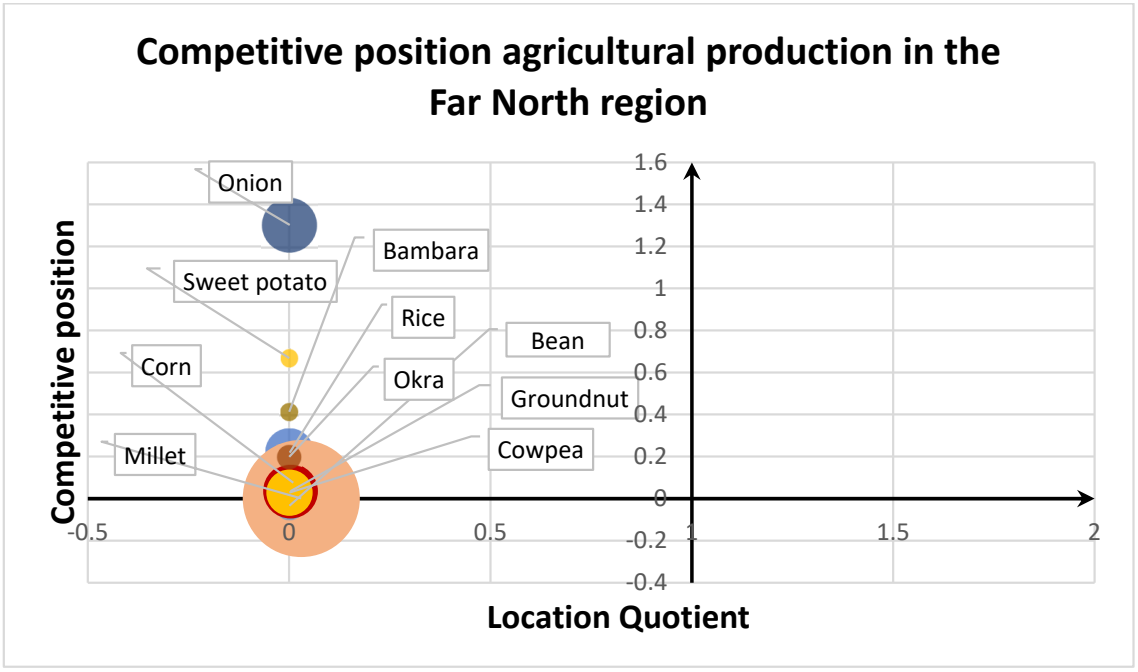


Figure 20. Competitive position of main products on average from 2009 to 2018 in the Far North region.

As shown in Figure 21, in the Central region, pineapple, sweet potato, sweet banana, plantain, yam, watermelons, manioc and potatoes are staple products. It is important to

note that some commodities are declining but not significantly, while other commodities are also experiencing insignificant growth. Non-commodities such as groundnuts, cucumbers, corn and macabo taro are experiencing slight growth. Rice and tomatoes, on the other hand, are not showing any significant decline. Farmers in the Central region face challenges such as land management, access to water resources, the use of modern farming techniques and access to markets. Initiatives can be put in place to support farmers and improve agricultural productivity, for example, by providing technical training and facilitating access to agricultural inputs. Farmers' organizations also play an important role in the region's agricultural production. They help to promote good farming practices, disseminate new techniques and defend farmers' interests.

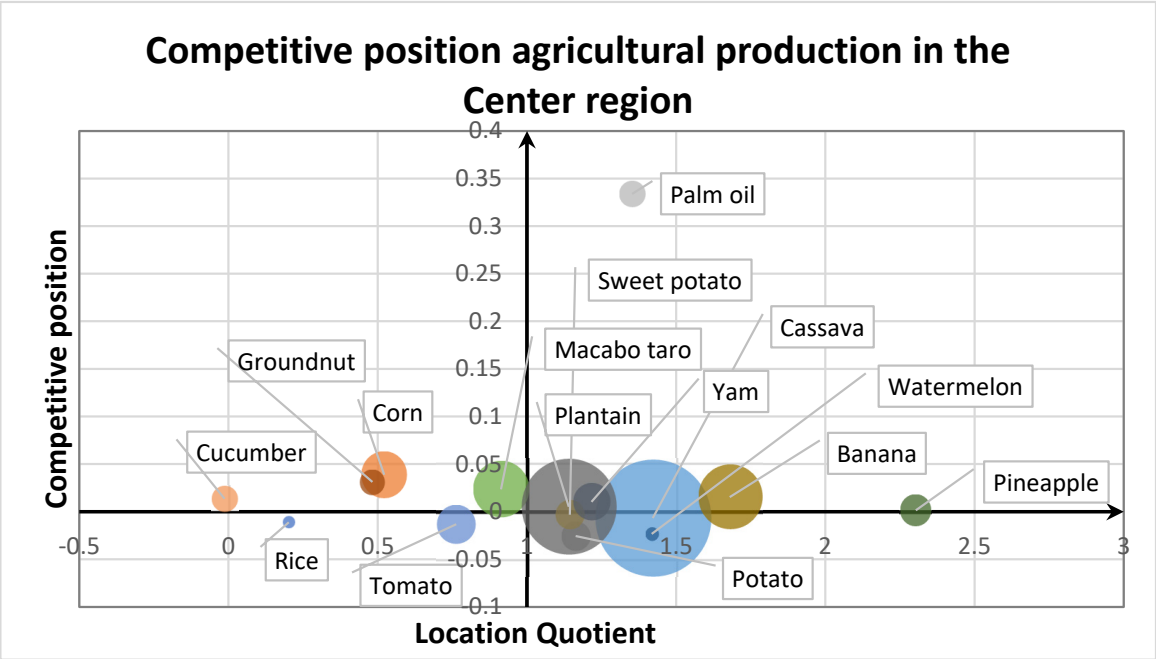


Figure 21. Competitive position of main products on average from 2009 to 2018 in the Center region.

Figure 22 shows ginger, plantain, macabao, palm oil, yam, sweet banana and pineapple as staples in the Littoral region. It is important to note that the sweet banana, in addition to being a staple, is also growing significantly. Beans, although not a staple, are growing significantly. Corn, cassava and sweet potatoes are non-basic products. The Littoral region enjoys a climate favorable to agriculture, with regular rainfall and moderate temperatures. This favors crop growth and enables relatively high agricultural yields. However, it should be noted that this region can also face agricultural challenges, such as deforestation, soil erosion and crop diseases. These challenges can affect agricultural productivity and require ongoing efforts to overcome. Framework policies would be necessary for sustainable production growth.

In Figure 23, the staple products in the northern region are millet, groundnuts, onions, maize, rice, sweet potatoes, cowpeas and potatoes. It should be noted, however, that the staple onion is enjoying significant growth. As for non-basic products, bean production is declining significantly. Macabao, taro and yam are showing slight growth, while cassava has grown significantly over the year under review. The region faces challenges such as poverty reduction, resource-related conflicts, food insecurity and the need to improve agricultural productivity. Mechanisms to alleviate these challenges could structurally improve production.

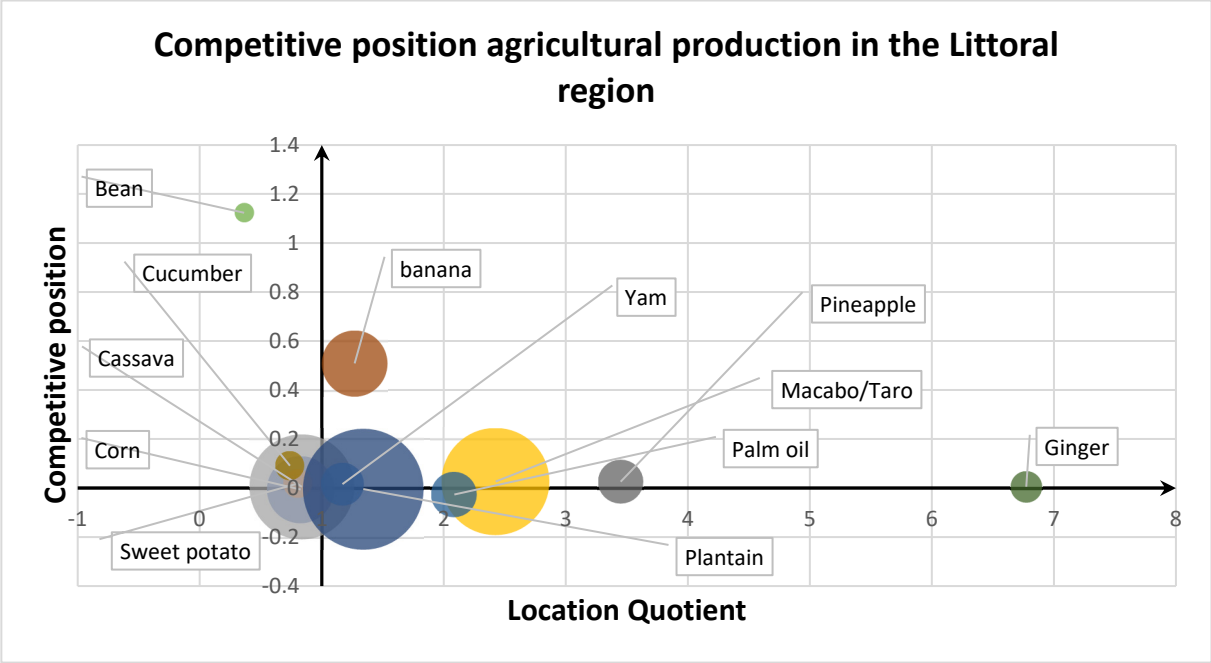


Figure 22. Competitive position of the main products on average from 2009 to 2018 in the Coastal region.

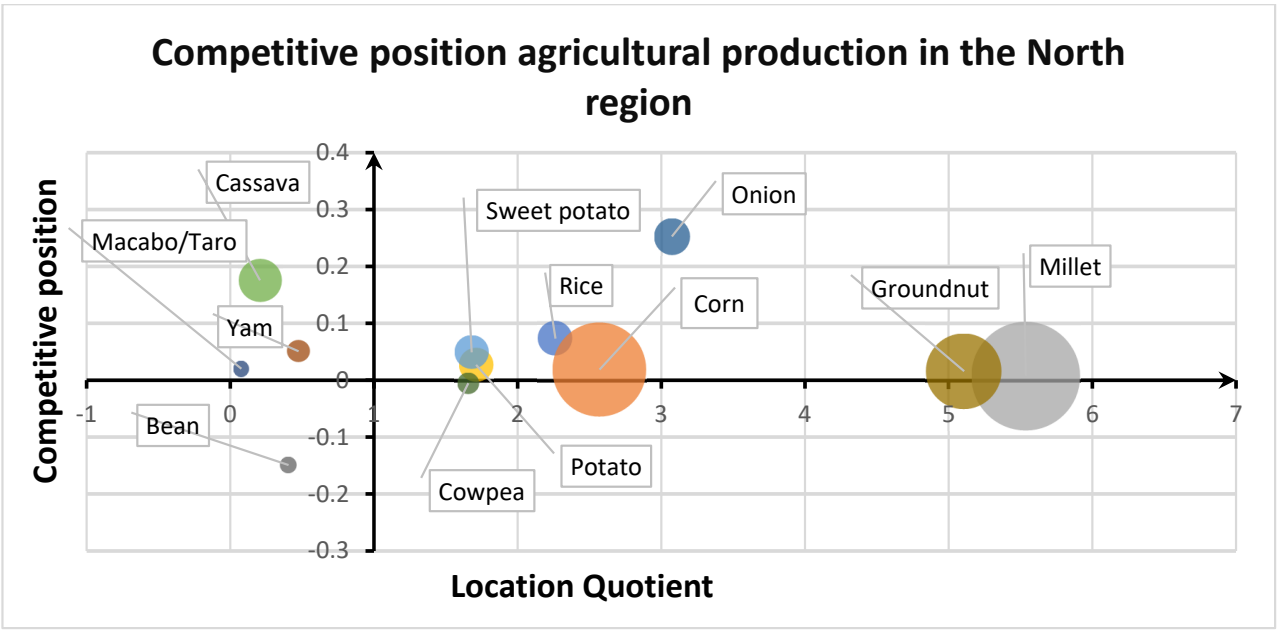


Figure 23. Competitive position of main products on average from 2009 to 2018 in the North region.

Figure 24 shows beans, ginger, soy, rice, sweet potatoes, palm oil, peppers, macabo taro, corn, potatoes, okra and bambara as commodities. It is important to note that no staple product is growing significantly in this region. On the other hand, non-basic products such as onions and pineapples are growing, while other products have shown slight growth. The security situation in parts of the Northwest region in recent years has had a significant impact on agricultural production. Conflicts, the non-operation of processing industries and population displacements can disrupt specific agricultural activities and limit access to arable land, having a negative impact on production.

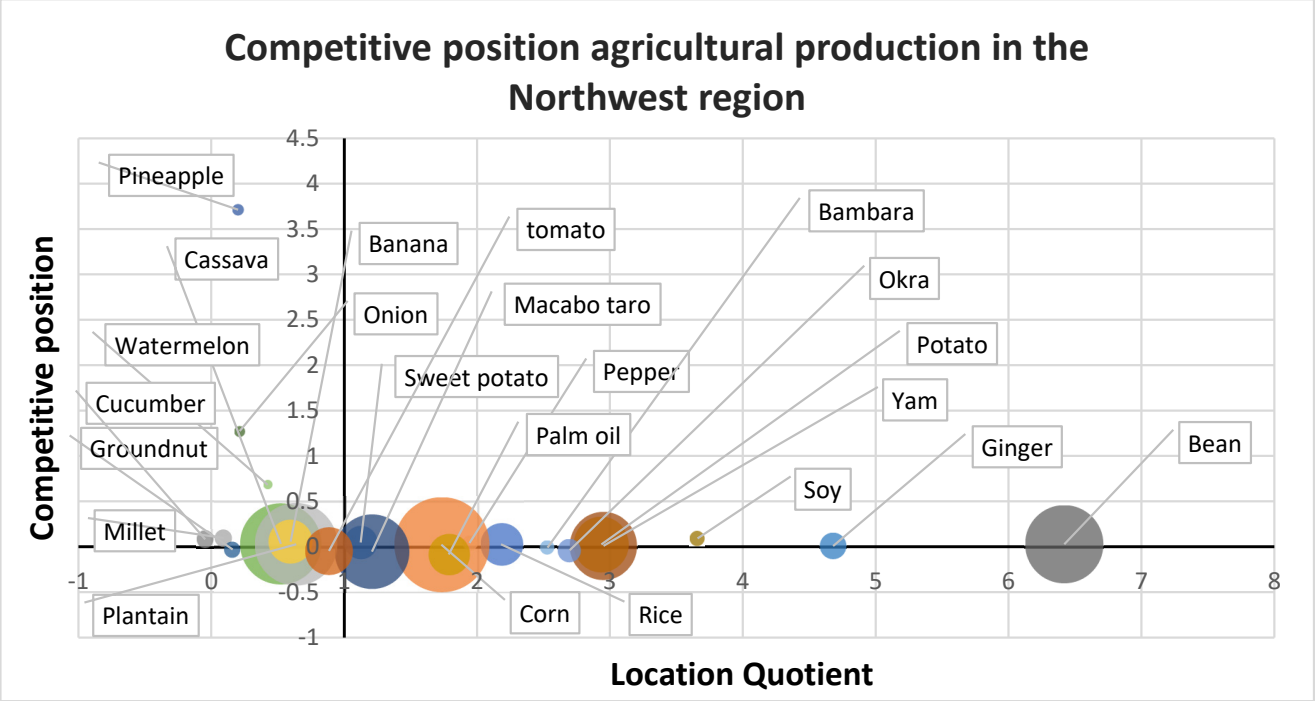


Figure 24. Competitive position of the main medium-sized products from 2009 to 2018 in the Northwest region.

Rice, palm oil, pineapple and groundnuts, as shown in Figure 25, are non-basic products that are growing rapidly in the West region. By contrast, tomatoes, watermelons, chilies, potatoes, beans, sweet potatoes, soy, sweet bananas and corn are the main staples. Tomatoes are the region's leading staple. It can also be observed that no single commodity showed significant growth throughout the study period. Cropping systems in West Cameroon may vary, but many farms still practice traditional methods. The West Cameroon region has high altitudes, creating a cool climate and favorable conditions for certain crops. It is important to note that the agricultural production situation can vary depending on a number of factors, including climatic conditions, local farming practices, access to resources and markets, and the agricultural support policies and programs in place in the region.

Figure 26 shows that the southern region still has a long way to go in terms of agricultural production, with cassava, plantain and okra as staples, which are growing significantly, and the rest of the non-basic products relatively variable and insignificant. The South Cameroon region is characterized by a humid tropical climate with high rainfall. While this can be beneficial for some crops, it can also lead to problems of excessive humidity and plant diseases. In addition, the region's soils can be acidic and of low fertility, which can limit agricultural productivity, a lack of infrastructure and access to markets, a lack of financing and technical support, and traditional farming practices. It should be noted that these factors may vary according to local specificities and the economic and social conditions of the region. Efforts to improve the agricultural infrastructure, increase access to markets, provide financial and technical support to farmers, and promote the adoption of sustainable farming practices can help to increase the agricultural production in the region.

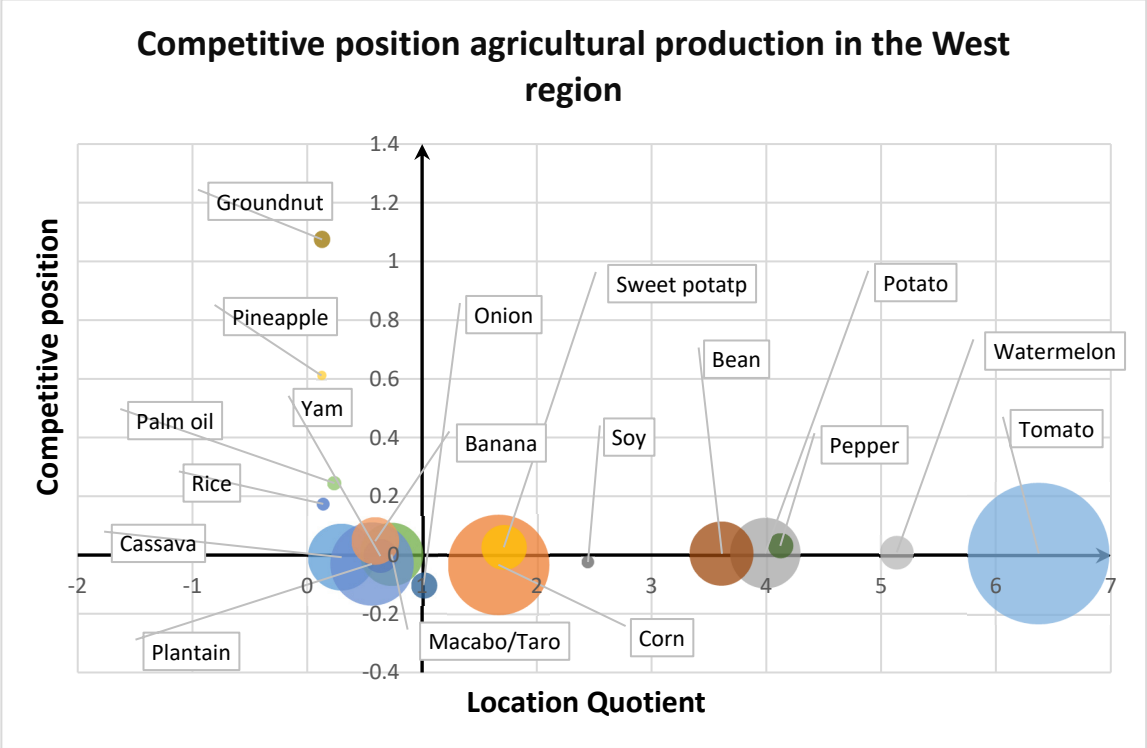


Figure 25. Competitive position of main medium-sized products from 2009 to 2018 in the West region.

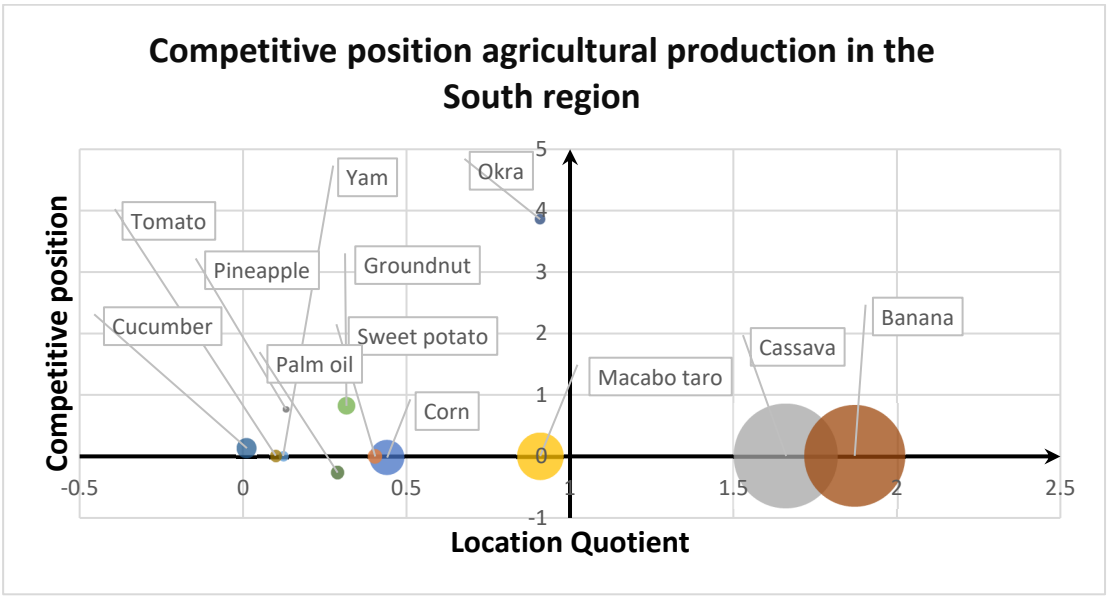


Figure 26. Competitive position of main medium-sized products from 2009 to 2018 in the South region.

Figure 27 shows palm oil, sweet bananas, manioc, corn, macabo, pepper and rice as the staple products in the Southwest region. These products should be given special attention in order to boost the sector and improve food availability in the region. Tomatoes and cowpeas are growing. Other non-basic products showed little significant variance.

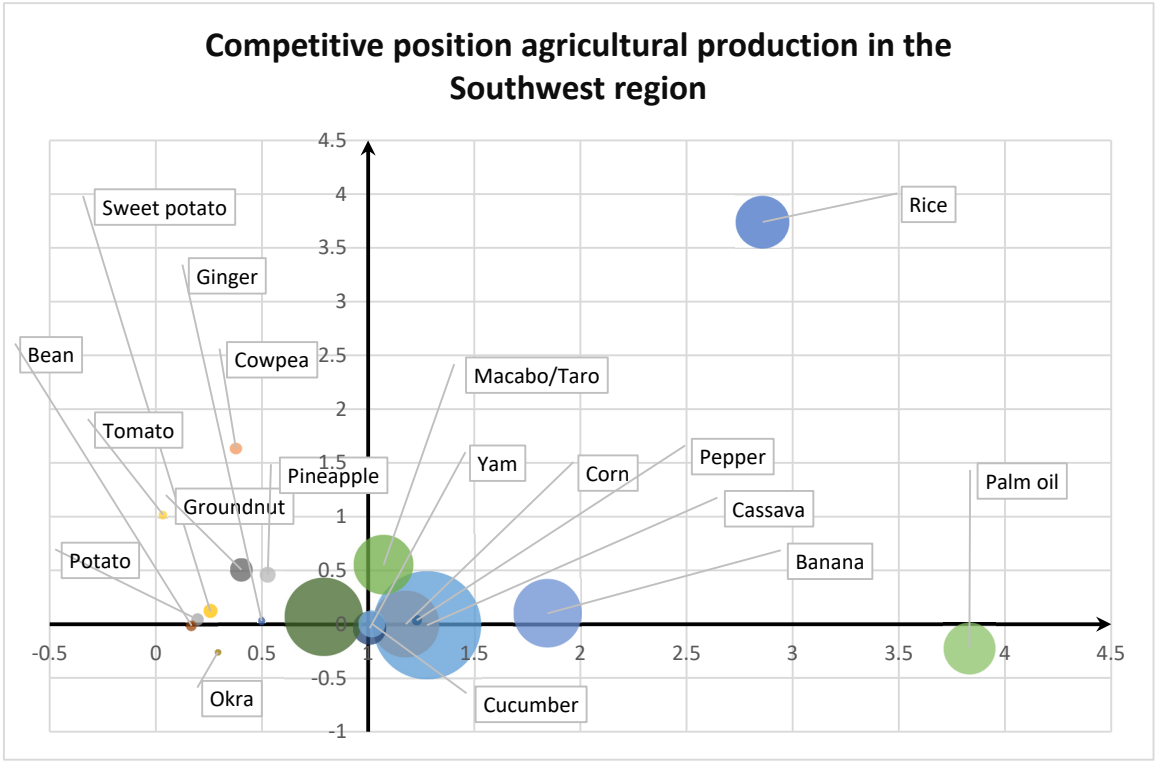


Figure 27. Competitive position of the main medium-sized products from 2009 to 2018 in the Southwest region.

Figure 28 shows the number of food-insecure people in Cameroon from 2014 to 2021 in two-year increments. Although overall agricultural production has remained on the rise throughout our study, the number of food-insecure people has also increased. More than half the population was food-insecure between 2014 and 2021. This increase can be explained by population growth that does not keep pace with agricultural growth, the non-diversification of staple food products, a lack of product exchange between regions, a high proportion of products devoted to export, rising food prices linked to energy prices and the COVID-19 pandemic. Accompanying mechanisms must be devised to improve these statistics.

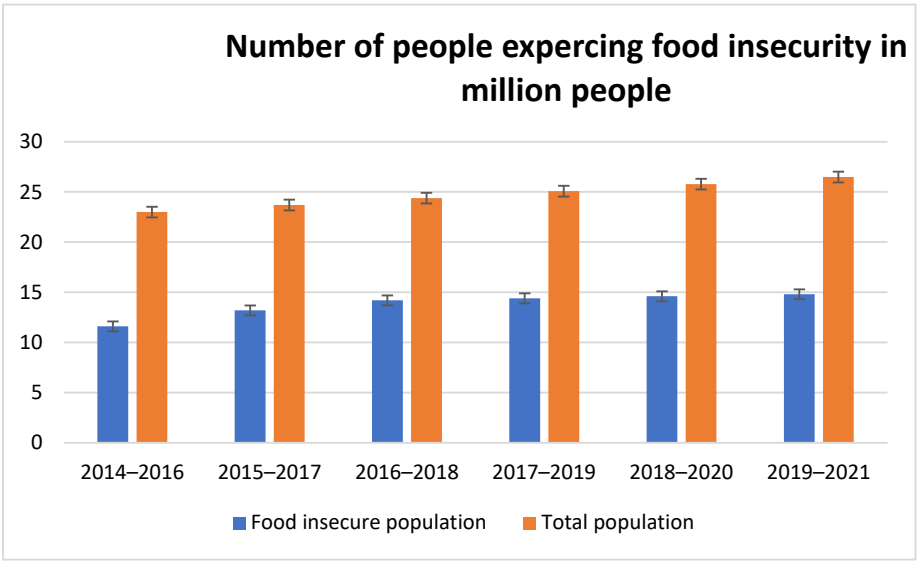


Figure 28. Number of food-insecure people in millions.

Figure 29 shows that between 2008 and 2014, the number of undernourished people declined from 1.7 million to 1.1 million, whereas between 2013 and 2021, the number of undernourished people rose from 1.1 million to 1.8 million. There are several reasons for this increase; either unemployment or population growth not keeping pace with food availability.

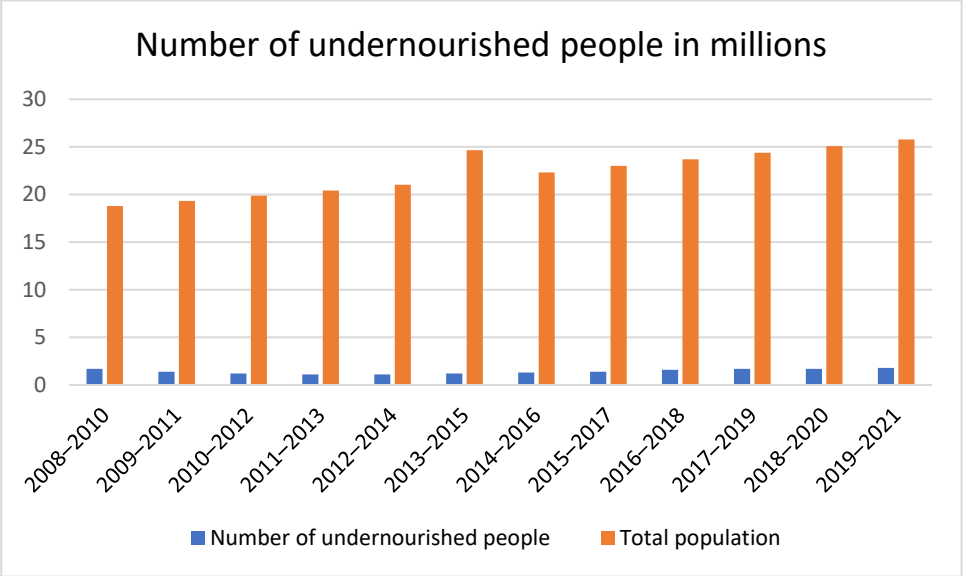


Figure 29. Number of undernourished people in millions.

Figure 30 aims to highlight the availability of local production by food product in Cameroon in tons of product per capita. It highlights food crops that are mainly produced locally and identifies those that are more dependent on imports. Cassava (0.21 tons per capita), on average, is heavily produced locally with high per capita availability, reflecting its importance as a staple food crop in the country. Locally produced rice averages 0.02 tons per capita, with very low local availability, which may indicate increased dependence on imports of this food crop. Corn (0.09 tons per capita) and millet (0.06 tons per capita), on the other hand, seem to be produced more locally, with moderate availability per capita compared with other crops. It should be noted that other factors such as real demand (domestic and foreign) and consumption can also influence the availability of agricultural products in the country.

An analysis of Figure 31 shows several interesting trends in population, production and capital income. The population growth rate has been declining over the years, from 2.8 in 2010 to 2.6 in 2018. The decline in agricultural production, lower investment, deteriorating infrastructure, increased security spending and loss of investor confidence are all significant factors in the observed demographic downturn. The agricultural production, for its part, is rather volatile, but there is a general downward trend from 9.8% in 2010 to 2.2% in 2018. The agricultural sector is impacted by many factors, such as environmental changes and economic difficulties. In addition, the displacement of farming populations due to conflict has forced many people to flee their farmland. This has led to a reduction in the available agricultural labor force and a drop in agricultural production. The destruction of agricultural infrastructure such as irrigation systems, storage warehouses and equipment damaged or destroyed during conflicts have hampered farmers' ability to cultivate and harvest their crops. The disruption of supply chains, such as roads and transport routes affected by conflict, makes it difficult to transport agricultural produce to market. These consequences have led to a decline in agricultural production in conflict-affected regions of Cameroon. Agriculture, an essential pillar of the Cameroonian economy, has been severely affected. The per capita food availability remained relatively stable throughout the period, with a constant value of 0.9 tons of food per capita. This suggests that despite fluctuating production, the per capita product availability remains constant. As a result, population

growth has slowed over the period under review, while agricultural production has shown a downward trend. However, the per capita product availability remains relatively stable. These trends may indicate a potential need to invest in sustainable and efficient agricultural practices to meet the needs of a growing population.

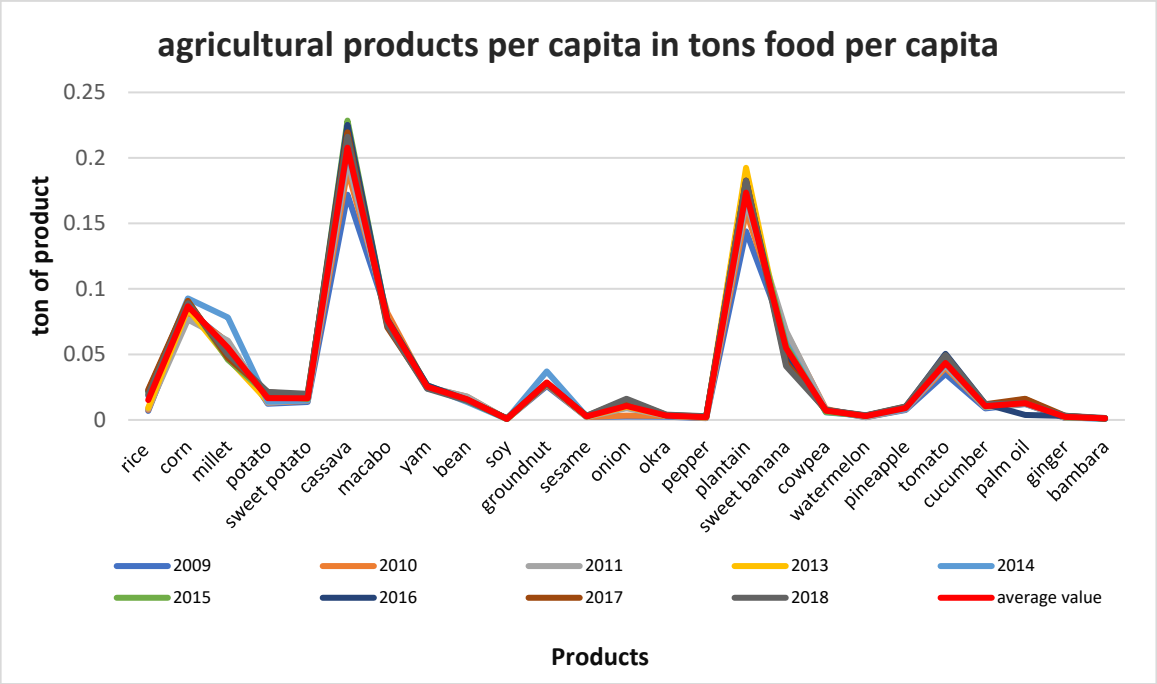


Figure 30. Agricultural products per capita in tons food per capita.

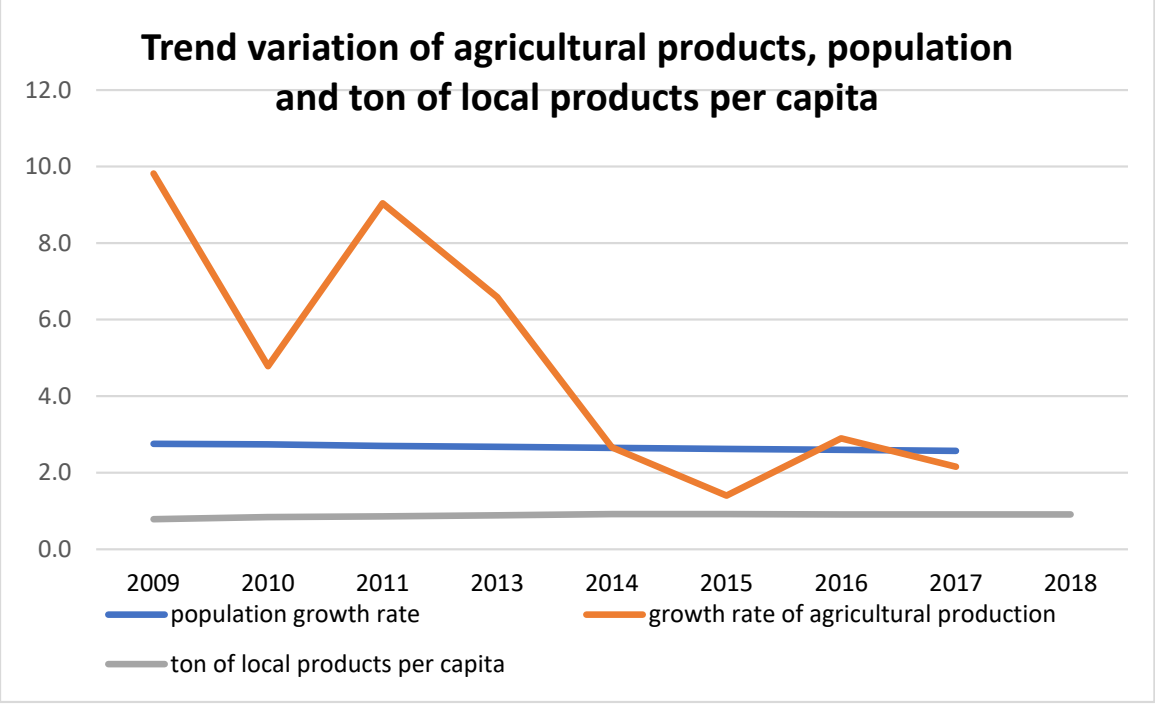


Figure 31. Growth rate of population, agricultural production and product.

5.8. Recommendation

To stimulate the local economy and contribute to sustainable agriculture, it is strongly recommended to do the following:

Invest in local agriculture: It is important to promote investment in local agriculture by providing financial, technical and logistical support to farmers. This will encourage increased local production and reduce dependence on imports.

Improving access to agricultural resources and infrastructure: It is essential to provide farmers with adequate access to land, water, quality seeds and modern agricultural technologies. Improving agricultural infrastructure, including rural roads and irrigation systems, will also facilitate the transport and marketing of produce.

Building farmers' capacities: By offering training and coaching programs to farmers, we will help them improve their skills in farm management, cultivation techniques, pest management and sustainable practices. This will help increase crop productivity and quality.

Encourage crop diversification: Promoting crop diversification can help reduce overreliance on certain crops and broaden the availability of local food products. This will contribute to food security by offering a wider variety of foods.

Encourage partnerships between players in the agricultural sector: Collaboration between farmers, research institutions, government agencies and non-governmental organizations is essential to share knowledge, technologies and best practices.

Invest in storage and processing infrastructure: Providing adequate storage and processing facilities will help to reduce post-harvest losses and add value to agricultural products while generating local added value.

Promote local consumption: Raising consumer awareness of the importance of supporting local food products and encouraging programs to promote local consumption can stimulate domestic demand and strengthen local agricultural markets.

The use of irrigation systems powered by renewable energies can save water and maximize irrigation efficiency, as well as being used to treat agricultural waste and produce biogas, drying crops and reducing greenhouse gas emissions. Renewable energies offer sustainable, economical and environmentally friendly solutions for agricultural production in Cameroon. They improve productivity, reduce costs and help preserve natural resources. By implementing these recommendations and suggestions, it will be possible to boost local agricultural production, reduce dependence on imports and strengthen food security in Cameroon. However, it is important to note that these measures must be supported by appropriate policies, targeted investments and the active participation of all players in the agricultural value chain.

6. Conclusions

A research approach aimed at quantifying, on the one hand, the contribution of each element of the energy–water–waste–land nexus to agricultural production and, on the other hand, a qualitative analysis of commodities and non-commodities by region was carried out, based on approaches and models applied in the literature. These analyses have produced a number of results, the main ones being as follows:

- The proportion of energy used in agriculture that comes from fossil fuels is 85%. Its average contribution is 0.42% in the agricultural production sector, which is beneficial to the ecobalance of the agricultural sector.
- A proportion of 67.88% of the total water abstraction is used for agricultural purposes. This has remained constant throughout the study period. The sector is managed in a sustainable manner and guarantees the long-term preservation of the resource.
- The Far North region has the largest harvested area (1,373,829 ha) and Adamawa (224,038 ha) the smallest. However, the Center region (4,334,095 tons) is the leading region in terms of agricultural production, while Adamawa (915,841 tons) produces the least; the Center, Littoral and West regions are more representative of diversified the agricultural production than the other regions; remarkable yields such as manioc (79. 60 t/ha, larger) in the Southwest are better than in the North (10.4 t/ha, smaller), yam (47.7 t/ha, larger) in the Center is better than (10.8 t/ha, smaller) in the

West, pineapple (66 t/ha, larger) in the Southwest is better than (0.11 t/ha, smaller) in Adamawa.

➢ The agriculture sector is growing at a slower pace, with more than half the population (11.6 million out of 23 million in 2009 to 14.8 million out of 26.5 million 2018) being food-insecure and 1.7 million malnourished over the study period. Further analysis of comparative figures and specific factors would be required to draw more robust conclusions and consider the structural measures to be taken. In our future work, we plan to develop a predictive model and the environmental and economic aspects of the various elements in the production chain.

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Nature-Based Solutions for Optimizing the Water–Ecosystem–Food Nexus in Mediterranean Countries

Silvia Vanino [1], Valentina Baratella [1,*], Tiziana Pirelli [2], Donato Ferrari [2], Antonella Di Fonzo [2], Fabrizio Pucci [2], Nikolaos P. Nikolaidis [3], Maria A. Lilli [3], Zübeyde Albayram Doğan [4], Tuncay Topdemir [4], Sami Awabdeh [5], Luna Al-Hadidi [5], Nabeel Bani Hani [5], Andreas Panagopoulos [6], Vassilios Pisinaras [6], Anna Chatzi [6], Estrella López [7], Christina Papadaskalopoulou [8], Dimitris Tassopoulos [8], Efstathia Chatzitheodorou [8], Alessandro Pagano [9], Raffaele Giordano [9], Ivan Portoghese [9], Esteban Henao [10], Anna Osann [10] and Stefano Fabiani [2]

1 Centro Agricoltura e Ambiente, Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria, Via della Navicella 2-4, 00184 Rome, Italy; silvia.vanino@crea.gov.it
2 Centro di Politiche e Bioeconomia, Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria, Via Barberini, 00187 Rome, Italy
3 School of Chemical and Environmental Engineering, Technical University of Crete, 73100 Chania, Greece
4 International Agricultural Research and Training Center (UTAEM), 35660 İzmir, Türkiye
5 National Agricultural Research Center (NARC), P.O. Box 639, Baq'a 19381, Jordan
6 Soil and Water Resources Institute (SWRI), Gorgopotamou Str., 57400 Sindos, Greece
7 Asociación Ecoadapta, 28012 Madrid, Spain
8 DRAXIS Environmental S.A., 54-56 Themistokli Sofouli Str., 54655 Thessaloniki, Greece
9 Consiglio Nazionale delle Ricerche-Istituto di Ricerca Sulle Acque (CNR-IRSA), Viale F. de Blasio, 5, 70132 Bari, Italy
10 AgrisSat Iberia SL, Paseo de la Innovación nº1, 02006 Albacete, Spain
* Correspondence: valentina.baratella@crea.gov.it

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Abstract: Nature-based solutions (NBSs), defined as actions that work with and enhance nature, providing environmental, social, and economic benefits, play a pivotal role in accomplishing multiple objectives within the Water–Ecosystem–Food Nexus domain. They contribute to facilitating the transition to more resilient agrifood systems and providing an evidence base for a broader Nexus policy dialogue. This paper describes the stepwise methodology developed in the EU-funded LENSES project to carry out a comprehensive analysis of NBSs in six pilot areas in five Mediterranean countries and presents the results of NBS implementation in four pilot areas, highlighting obstacles and opportunities. The methodology includes the development of an analytical evaluation framework and a comprehensive catalogue of Nexus-related NBSs, whose suitability needs to be assessed at the local level to achieve better use of protected/natural ecosystems, increase the sustainability and multifunctionality of managed ecosystems, and design and manage novel ecosystems. Subsequently, in a collective learning process that supported the operationalisation of the WEF Nexus, NBSs were identified that address specific contextual vulnerabilities, improve water distribution, and enhance food security while preserving ecosystems and supporting adaptation to climate change. The added value of the proposed methodology lies in the multi-stakeholder participatory approach to gain in-depth knowledge of local agri-food systems, including their main WEF-related challenges, and to facilitate overcoming barriers to NBS implementation. Finally, a final survey was conducted among a small group of purposively selected stakeholders to gain some insight into their perceptions of the impact of NBS and to gather some opinions on the main barriers and opportunities.

Keywords: nexus; sustainability; biodiversity; water-food security; resilience; water distribution; food security; ecosystem services

1. Introduction

This study aims to understand the Water–Ecosystem–Food (WEF) Nexus approach and demonstrate its application in Mediterranean countries. Policymakers are paying more and more attention to the WEF Nexus because water, energy, food, and ecosystems are the cornerstones of long-term societal and economic stability, as they provide the foundation for public well-being, the welfare state, peace, and security [1,2]. Yet, as the global population and urbanization continue to surge, so does the demand for these essential resources. The world faces the unprecedented challenges of extreme weather events and shifting climatic conditions, which further threaten resource security and the integrity of ecosystems [3,4].

The Mediterranean area, in particular, is exposed to a multiplicity of stresses, from water scarcity to water pollution, degradation of natural resources, high levels of food loss and waste, and increasing demand for energy and food. In this context, integrated management strategies centred on the WEF Nexus approach offer a useful path to address resource issues. However, agricultural practices, urban development, water demand, and protection of ecosystems are areas of specific interest for the decision-makers, who are responsible for defining interventions aimed at enhancing the availability of water for various competitive water uses. Under this perspective, it becomes widely clear that addressing challenges related to water, food, and ecosystems in isolation is not appropriate [5]. Rather, a holistic, integrated, and cross-cutting approach is required, as embodied by the WEF Nexus. The WEF Nexus underscores the interdependence of water, food, and ecosystem security. This approach identifies mutually beneficial responses based on an understanding of the synergies between water, ecosystem, and agricultural policies while also highlighting potential conflicts and unintended consequences. It offers a transparent framework for assessing trade-offs and synergies that protect the sustainability of ecosystems while aligning with long-term economic, environmental, and social objectives. Therefore, adopting a WEF Nexus is not merely a choice but emerges as essential to pave the way for a green economy while striving to achieve the Sustainable Development Goals (SDGs) [6].

Nonetheless, the transition from theory to practical application using the WEF Nexus approach is not straightforward and entails multiple difficulties. Implementing this approach requires collaboration among diverse sectors and stakeholders, demanding a coordinated effort [7]. Stakeholders play an important role in assessing the WEF Nexus, as many policy choices affect their ability to make use of environmental goods and ecosystem services [8]. The challenge lies in persuading communities, decision-makers, and the private sector to embrace a holistic Nexus approach rather than pursue disjointed sectoral actions, which brings a wide range of collective benefits [9]. To overcome this barrier, researchers need to expand their toolkit to provide policymakers with compelling demonstrations of Nexus solutions. For the management of the WEF Nexus, increasing attention is being directed towards the employment of Nature-Based Solutions (NBSs), especially in regions dealing with challenges related to water scarcity and environmental degradation [3,10].

NBSs for climate change adaptation and disaster risk reduction can be defined as actions that work with and enhance nature to restore and protect ecosystems, to help society adapt to the impacts of climate change, and to slow further warming while providing multiple additional benefits (environmental, social, and economic) [11,12]. While not an entirely novel concept, the prominence of NBSs gained momentum in the early 2000s. Initially conceptualized as a nature-centric response to climate change challenges, it garnered support from influential entities like the International Union for Conservation of Nature [13]. Subsequently, the European Commission recognized the imperative of establishing a term that embraces the various existing approaches. NBSs operate as an overarching concept, encompassing a spectrum of terminologies, including ecosystem-based approaches, ecosystem-based adaptation, ecosystem-based disaster risk reduction, green infrastructure (both blue and green), and sustainable management (including ecosystem-based and sustainable forest management) [14,15].

NBSs, which protect and restore natural ecosystems and/or utilize diverse native species, can play a key role in ensuring climate change mitigation and adaptation services

while also contributing to cultural ecosystem services such as inspiration and learning from nature [16].

NBSs play a crucial role in tackling the interconnected challenges within the WEF Nexus. These approaches utilize natural processes to achieve a balanced and sustainable management of water, ecosystems, and food resources. Over the past decade, the term NBSs has surged in popularity, mirroring the amplified acknowledgment of nature's pivotal role in providing a wide range of benefits to human communities across local, regional, and global scales through sustainable socio-ecological systems [17]. The essence of NBSs lies in their inherent multifunctionality, serving as solutions that yield manifold environmental, social, and economic advantages. They intricately interlink disaster risk reduction, climate change mitigation and adaptation, and the restoration and safeguarding of biodiversity and ecosystems within sectoral interventions and policies.

2. State of Art

It is widely recognized that the implementation of NBSs within the framework of the WEF Nexus requires a robust policy and governance framework that can effectively address the complex interactions between natural resources and social systems [1,13].

Several research studies have addressed the WEF Nexus theme, discussing how the approach can be effectively implemented on the ground [18–20]. On the other hand, there is still a significant lack of understanding of the principles for the design and implementation of NBSs, as well as of methodologies and evaluation frameworks for assessing the effect and impact conditions of NBSs [16,21]. Stakeholder engagement and the socio-environmental effectiveness of NBSs are also relatively under-researched, highlighting a major knowledge gap in the relationship between NBSs and society, especially in rural areas [16,21–24].

Currently, the majority of scientific research on NBSs has been conceptual, offering either principles and frameworks for implementation and/or assessment, or reviews of the origins and use of the concept, with little empirical research [22,25–27].

However, NBSs are being applied in different parts of the world and at different scales, with a predominance of top-down approaches and a need for more participatory approaches to the planning and implementation of NBSs to effectively deliver environmental and societal benefits [28,29]. This study presents the results of the comprehensive analysis carried out within the project "LENSES—LEarning and action alliances for NexuS EnvironmentS", funded by the European Union under the "PRIMA Foundation" programme. In five Mediterranean countries—Greece, Italy, Jordan, Spain, and Turkey—a participatory approach [23], intended as the interaction and engagement strategies aimed at involving stakeholders, was applied to analyse the WEF Nexus challenges affecting six pilot areas and to identify appropriate NBSs, as well as to gather information on barriers and opportunities for their implementation. A catalogue of NBSs was built and refined through careful consideration of the manifold challenges faced in the different geographical areas. This comprehensive assessment facilitated the identification and subsequent selection of the most relevant NBSs, the ones that, better than others, could help in tackling the specific local challenges.

Our paper contributes to the existing literature by advancing the efforts both from (i) the methodological point of view and (ii) evaluating the implementation of NBSs in response to identified WEF challenges and their impact on selected pilot areas.

We developed a stepwise methodology for the comprehensive analysis of NBSs in Mediterranean countries and implemented the methodological framework for participatory approaches that we developed in Baratella et al. [23] to identify and deeply analyse the WEF Nexus challenges. As a fundamental added value, after developing the analytical evaluation framework and the comprehensive catalogue of WEF-related NBSs, we implemented the identified solutions in four pilot areas to assess at the local level the improvement of the sustainability and multifunctionality of managed agro-ecosystems.

3. Materials and Methods

3.1. Pilot Areas and Main Challenges

Six pilot areas were selected across five Mediterranean countries (i.e., Greece, Italy, Jordan, Spain, and Turkey). In general, the challenges affecting the selected pilot areas mainly relate to competitive water and land uses in agrifood systems aimed at food production, conservation of forests and natural ecosystems, recreational (e.g., tourism), and other activities (industrial production, etc.). All pilot areas represent typical Mediterranean conditions in terms of, e.g., climate conditions and climate change impacts, interaction between surface water and groundwater, competitive uses of the resources, relevance of agricultural activities, types of crops, social context, and stakeholders. Figure 1 shows the pilot locations, while their background and specific challenges are described in Table 1.



Figure 1. Location of pilot areas across the Mediterranean basin.

Table 1. Overview of pilot areas across the Mediterranean basin.

Name of the Pilot Area, Region and Country	Short Description	WEF Challenges and Conflicts
Koiliaris River watershed (Crete, Greece)	- Hydrological and water quality monitoring systems are operating. - Agriculturally productive areas, with pastures and forests.	- Poor water management under climate change; - Soil degradation and water erosion due to deforestation for cropping and livestock grazing; - De-vegetation and inappropriate cultivation practices; - High energy costs (pumping); - Tariff change: transition to full water cost recovery.
Pinios River Basin (Agia and Pinios River Delta watersheds, Thessaly, Greece)	- Key agricultural areas of the most productive basin of Greece, with fertile soils accompanied by dry summer climates that require high irrigation inputs of water.	- Groundwater over-abstractions for irrigation for Agia. Surface water is mainly used for irrigation in Pinios River Delta, with infrastructure of low efficiency, causing possible problems in environmental flow maintenance. - High energy costs (pumping) in both watersheds. - Agriculture competes with tourism along the coastline in Pinios River Delta. - Droughts significantly affect water availability in both watersheds. - Complex groundwater salinization processes are met in Pinios River Delta.

Table 1. *Cont.*

Name of the Pilot Area, Region and Country	Short Description	WEF Challenges and Conflicts
Tarquinia Plain (Lazio Region, Italy)	- Intensive agriculture (both irrigated and permanent crops) and tourism (archaeological sites) are the main activities. - Protective saline areas.	- Water quality and quantity management. Groundwater pollution due to Nitrates; - Soil degradation - High energy costs for water pumping; - Economic farm situation; - Limited support for tourism.
Gediz Basin, Menemen Plain and Delta (Aegean Region, Türkiye)	- Agricultural activities (vegetables and fruit trees) and forested/semi-natural areas (52% and 45% of the area); - RAMSAR wetland Bird sanctuary.	- Demographic development, urbanization, industrialization, and irrigation cause water scarcity. - Periodic water shortage due to drought and unconscious excessive use of water. - Multiple water uses: agricultural, industrial, domestic; - Groundwater depletion and soil salinity; - Economic viability.
Doñana National Park area, Guadalquivir basin (Andalucia Region, Spain)	- Natural reserve in South Andalusia; - Marshlands and lagoons with high biodiversity; - Horticulture and intensive berry production, which require significant groundwater volumes; - Importance of nature tourism (e.g., birdwatching; UNESCO biosphere reserve).	- Land and water use conflict involving environmental conservation, intensive agriculture, tourism, and administration; - Illegal abstractions of water and poor aquifer management; - Intensive greenhouse irrigated agriculture has a significant impact on groundwater (overexploited and polluted); - Improved Governance: European consumers' concerns regarding the impacts of irrigation on ecosystems and intensive farming in society have led to the active involvement of supermarkets to ensure the legal and sustainable use of water. Support transition to less intensive yet profitable models ("Doñana label"); - Preserve biodiversity while dealing with sea level rise, saline intrusion, climate change impacts, etc.
Middle Jordan Valley (Deir-Alla Region, Jordan)	- Intense agricultural activities: vegetables and fruit trees; - Non-conventional water resources: Mixed, saline water and rainfall for irrigation; - Desalination helps improve water quality; - Solar energy is already used for irrigation and desalination.	- Water quality/quantity management; - Soil degradation: salinization, inefficient irrigation, and erosion; - Limited economic potential for new technology in agriculture and high energy cost; - Conflicts due to limitations in water allocation to farmers; - High post-harvest losses, inefficient markets, food safety, and difficulties in ensuring production quality standards.

Following the methodological framework for a participatory process to explore Nexus-related challenges described by Baratella et al. [23], multistakeholder groups were established at the local level, ranging from policymakers to farmers and other end users: key actors were sampled across Nexus domains using an exploratory qualitative approach. Snowball sampling and semistructured interviews were then used to extend the coverage to a cross-section of stakeholders involved in natural resource use and management at different levels.

Identified stakeholders were involved in three main phases during the assessment of NBSs: at the beginning of the activities, the multistakeholder groups identified the WEF challenges of their pilot areas through tailored participatory activities, which included

Participatory Mapping and System Dynamics Modelling [23,30]. Then, the actors defined the NBS adapted to be applied in their study area, and finally, a small group of actors, purposely selected according to previous interviews among those more interested and/or directly involved in the implementation of NBSs [22,23], responded to a questionnaire to give their opinion on the impact of NBSs and define the main barriers and opportunities of the NBS implementation. The final evaluation survey, although with a small number of respondents, suggests that NBSs can be seen as a tool to improve water distribution and enhance food security while preserving ecosystems and supporting adaptation to climate change. For more details on the participatory methodologies used, see Baratella et al. [23] and Yaseen et al. [31]. In 3 pilot areas (Greece, Jordan, and Turkey), some NBSs were implemented at the field level, and results were collected.

3.2. Catalogue on Nature-Based Solution

The participatory process of NBS selection and analysis to support Nexus optimization is based on a (public) NBS catalogue accessible online to a wide range of stakeholders, including decision-makers. The catalogue includes a list of 54 available NBS along with additional information (type, ecosystem services, challenges, and SDGs) explained in specific factsheets that users can explore.

The first step in this process was to critically review existing frameworks for assessing adaptation/resilient WEF Nexus options for rural areas (Step 1). The review aimed to identify commonalities and gaps in existing frameworks for addressing the WEF Nexus, as well as their applicability at different spatial scales. Following the review, a WEF Nexus framework was drafted to assess ecosystem services provided by NBS (Step 2). This framework was modified into a user-friendly module (nbscatalogue.lenses-prima.eu) to allow the selection of NBS and was built on available methodologies and information for selecting NBS [32,33]. This "WEF Nexus assessment framework" was used to develop the NBSs Tool (Step 3).

The conceptual design of the WEF Nexus-appropriate framework for the assessment of resilience enhancement options, presented in Figure 2, was built upon and adapted to the NBS classification scheme developed within the Thinknature project [32]. The NBS classification scheme was a result of a synthesis conducted from a literature review and stakeholder consultation/discussion on the ThinkNature platform.

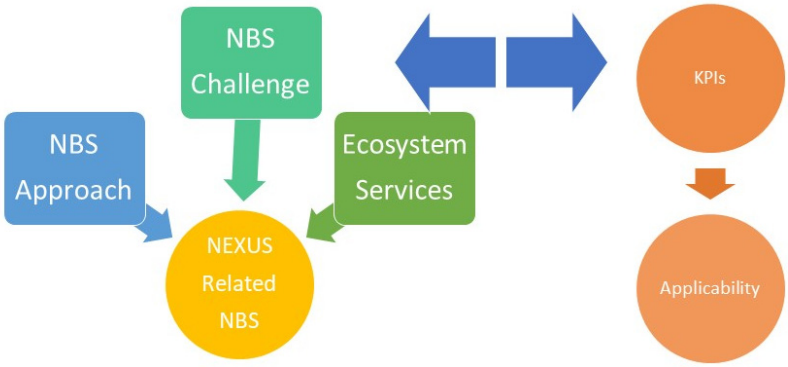


Figure 2. Design of NBS WEF NEXUS evaluation framework.

To help practitioners navigate the landscape of NBS selection and assessment, a roadmap has been developed, and the NBS practitioner must follow a step-by-step approach. The phases of this approach are described below and illustrated in Figure 3.

The first phase of the roadmap is the development of a vision for the landscape. This vision drives the project and enables potential local stakeholders to achieve consensus and overcome the many barriers that will arise from its implementation. To develop such a vision, it is critical to identify the environmental and ecological problems of the region and define a holistic solution that will add value to the region and enhance its resilience. This

vision brings local stakeholders and decision-makers on board to materialize the project [34]. The identified challenges the area/basin under consideration is facing regarding the WEF Nexus can be viewed at this stage separately for each component of the Nexus. Once the challenges of the different pilot areas have been identified, a primary list of appropriate NBSs that address the vision for the landscape and the challenges were identified for each pilot area using the module (https://nbscatalogue.lenses-prima.eu/ (accessed on 12 March 2024)). Applying the WEF Nexus Evaluation Framework, it is possible to identify the desired ecosystem services to obtain from the landscape as well as the approaches needed to improve ecosystem services. Finally, for each of the selected NBSs, related Key Performance Indicators (KPIs) were identified in order to assess their technical effectiveness in improving service under specific conditions, the climate resilience of the solution, and their contribution to adaptation. The selections made should be consistent with the vision built in the first phase. A stakeholder consultation (focus groups) was conducted on the selected WEF-optimized NBSs to revise and finalize the NBS list in each pilot area.

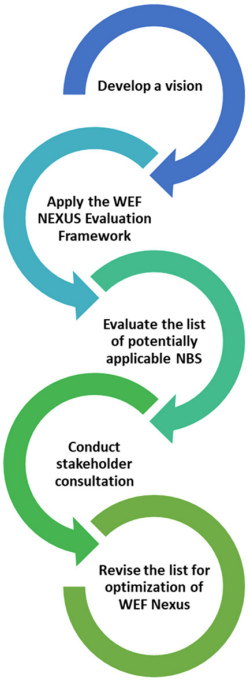


Figure 3. Augmented roadmap to help the practitioners navigate the landscape of NBS selection and assessment.

Finally, a module for decision support on Nexus-related NBS selection, and the methodology that was followed for the implementation of the tool were developed. It is a catalogue holding a list of existing nature-based solutions, making them available to the wider public. Stakeholders should be able to access an evidence-based framework as well as guidance to select solutions that incorporate nature-based approaches to increase the resilience of the water–energy–food Nexus. The module for decision support on Nexus-related NBSs selection allows the selection of NBSs and is built on available methodologies and information for selecting an NBS. At the same time, it provides KPIs to assess their technical effectiveness, effectiveness in improving service under specific conditions, climate resilience of the solution, and contribution to adaptation. The KPIs used in the module were adapted from the EU Handbook for practitioners [33]. Furthermore, the user is able, through an easy-to-use and user-friendly interface, to explore a list of available NBSs, search by keyword to find a specific NBS, as well as use filters for the attributes of the NBSs to narrow down their results.

NBSs are categorized into 3 groups of type, sub-types, and NBS types. The type groups and sub-types selected by the different stakeholders in the pilot areas are shown in Table 2.

Table 2. NBSs selected for different pilot areas, categorized by Group and Sub-type.

Group Types	Sub-Types	NBSs Type	#
Type 1—Better use of protected/natural ecosystems	Monitoring	Assessment of NBS benefits	1
		Ecosystem services evaluation methods	1
		Regular monitoring of bio-indicators	1
			3
	Protection and conservation strategies in terrestrial, marine, and coastal areas ecosystems	Ensure continuity with ecological network (protection from fragmentation)	2
		Limit or prevent specific uses and practices	2
		Maintain and enhance natural wetlands	2
		Natural Protected Area network structure	1
		Protect forests from clearing and degradation from logging, fire, and unsustainable levels of non-timber resource extraction	1
			8
Type 2—NBSs for sustainability and multifunctionality of managed ecosystems	Agricultural landscape management	Incorporating manure, compost, biosolids, or crop residues to enhance carbon storage	7
		Increase soil water holding capacity and infiltration rates	6
		Agro-ecological practices	5
		Soil improvement and conservation measures	5
		Agro-ecological network structure	3
		Change crop rotations	3
		Enrichment planting in degraded and regenerating forests	2
		Mulching	4
		Use soil conservation measures: Cover crops; Deep-rooted plants and minimum or conservation tillage; Agroforestry; Wind breaks	4
		Implementation of hedges and planted fences.	2
		Implementation of soil improvement and conservation measures	1
		Use grazing management and animal impact as farm and ecosystem development tools	1
		Produce and integrate biochar into agricultural soils	1
		Flowers strips	1
		Forest patches	1
			46
	Coastal landscape management	Integrated coastal zone management	1
			1
Type 3—Design and management of new ecosystems	Ecological restoration of degraded terrestrial ecosystems	Plant trees/hedges/perennial grass strips to intercept surface run-off	2
		Soil and slope revegetation	2
		Strong revegetation measures for steep slopes	2
		Systems for erosion control	2
		Utilization of pre-existing vegetation	1
			9
	Restoration and creation of semi-natural water bodies and hydrographic networks	Floodplain restoration and management	2
		Re-vegetation of riverbanks	2
		Reconnect rivers with floodplains to enhance natural water storage	1
		Restore wetlands in areas of groundwater recharge	1
		Rivers or streams, including remeandering, re-opening Blue corridors	1
		Restoration and management of floodplains	1
			8

After the selection of different NBS types by the researcher and main stakeholders of the several pilot areas, in selected cases (Greece, Turkey, and Jordan), some NBSs were implemented. In Spain and Italy, NBSs were not implemented, but recognizing the importance of local knowledge and engagement, a participatory approach was emphasized to ensure that the chosen NBSs aligned with the needs and aspirations of the pilot commu-

nity. By involving local stakeholders, such as farmers, landowners, and residents, in the decision-making process, a collaborative environment was fostered, promoting a sense of ownership and shared responsibility for the successful implementation of NBSs.

3.3. Stakeholder Survey on NBS Implementation

After NBS implementation and the analysis of the first results in the different areas, a survey was conducted of a limited number of stakeholders, selected as a subset of the larger groups involved in the previous phases of engagement, to gain some insight into stakeholders' interest and perceptions of the performance of NBSs in the systems under study.

Data were collected through individual online or face-to-face surveys, virtual interviews, and web meetings. A questionnaire was developed to collect data about NBS implementation. This survey, designed as a tripartite framework, reflects a tailor-made approach that takes into account the different dimensions of the project. This structured questionnaire is distinctly separated into three sections (Figure 4). The initial and final segments remain uniform across all stakeholders, fostering coherence and inclusivity, while the pivotal middle section dynamically adapts to the selected challenge (water, food, or ecosystem). The first section begins with some information on the identification of the stakeholders and their roles within the scope of the project. It lays the groundwork for understanding their engagement with NBSs corresponding to the specific challenge they choose. The user then selected the next section, which was tailored to the chosen WEF challenge. For example, stakeholders choosing the water sector will encounter questions specific to the strategies, experiences, and outcomes of water-centred NBSs. Likewise, those engaging with the Food challenge are presented with inquiries probing the efficacy of NBSs in addressing food-related challenges, and similarly for the ecosystem challenge.

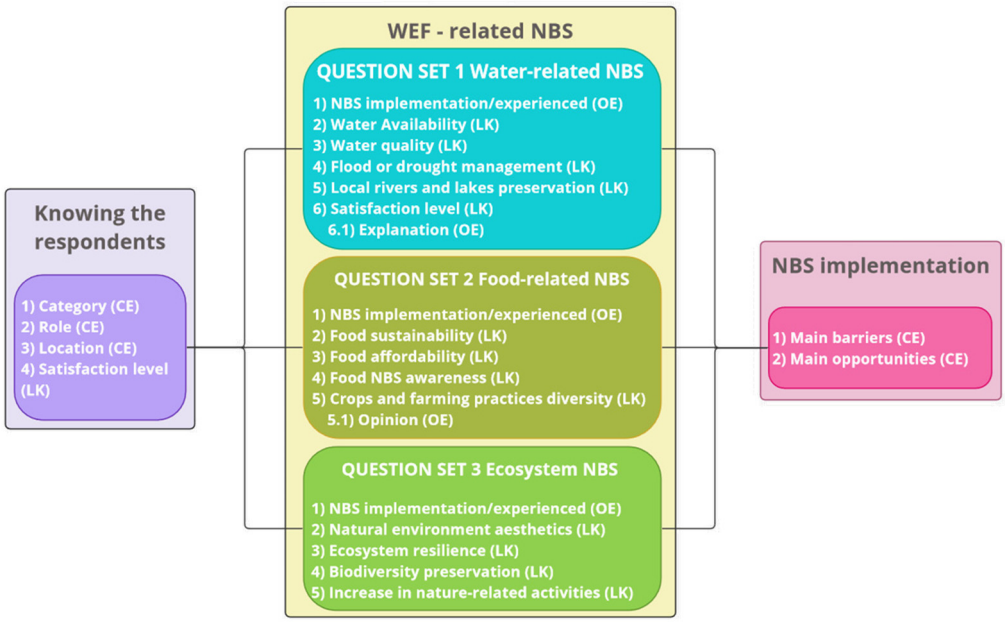


Figure 4. Design of NBS assessment questionnaire, CE = close-ended question, OE = open-ended question, LK = Likert question.

The final section is common to all stakeholders, presenting a set of overarching questions, which also include the selection of which barriers and opportunities are related to the implementation of NBSs in their pilot rural areas. This universal section aims to amalgamate diverse perspectives and experiences, fostering an environment for stakeholders to share their proposals, suggestions, and insights that transcend the confines of specific challenges. This comprehensive tripartite structure not only facilitates domain-specific

insights but also affords a panoramic view of stakeholders' collective experiences, enriching the project with multifaceted viewpoints and recommendations.

The questionnaire is available as Supplementary Materials to this article.

3.4. Data Analysis

The Likert scale was selected because it offers several positive aspects: (i) greater sensitivity in measuring participants' opinions or attitudes; (ii) greater flexibility for participants to provide responses that better reflect their opinions or perceptions; (iii) greater resolution in the data. In fact, using a 7-level scale can lead to richer and more detailed data, allowing for more in-depth and informative analyses.

4. Results

4.1. NBS Catalogue

In this study, the Module for decision support on Nexus-related NBS selection is presented. It is a catalogue holding the list of 54 existing nature-based solutions (NBSs), making them available to the wider public. Stakeholders should be able to access an evidence-based framework as well as guidance to select solutions that incorporate nature-based approaches to increase the resilience of the water–energy–food (WEF) Nexus. The module for decision support on Nexus-related NBS selection allows the selection of NBSs and is built on available methodologies and information for selecting an NBS. At the same time, it provides key performance indicators (KPIs) to assess their technical effectiveness, effectiveness in improving service under specific conditions, climate resilience of the solution, and contribution to adaptation. NBS selection is also envisaged with the United Nations' Sustainable Development Goals (SDGs), which include specific targets and indicators that could be achieved by implementing specific NBSs, as well as real case examples.

The NBS framework is based on research around innovation actions that highlight the multifunctional role of NBSs and their potential ability to fulfill multiple social, economic, and environmental goals. The tool is publicly available on the LENSES project website (https://www.lenses-prima.eu/ (accessed on 12 March 2024)) at this link: https://nbscatalogue.lenses-prima.eu/ (accessed on 12 March 2024) (Figure 5).

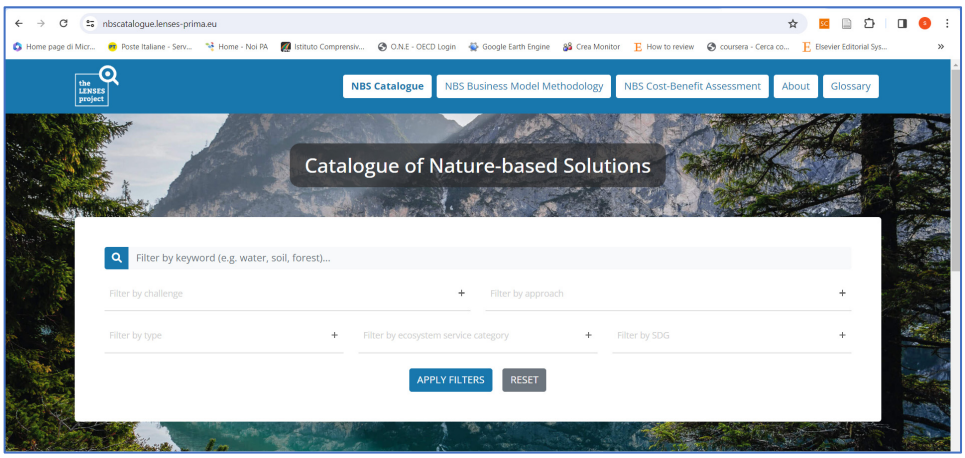


Figure 5. Catalogue of nature-based solution interface on LENSES website (https://nbscatalogue.lenses-prima.eu/ (accessed on 12 March 2024)).

4.2. Water–Ecosystem–Food Challenges

The stakeholders were selected to guarantee a good balance among the different sectors (i.e., water, food, and ecosystems), the role (e.g., policymakers, public and private decision-makers, citizen organizations, academia, etc.), and including all institutional and governance levels that might be relevant to the issues at stake (i.e., national, regional, and local) (Figure 6). The following Table 3 includes a summary of the stakeholders involved

(per sector) and interviewed to define the main challenges of their areas and to select the most suitable NBSs.

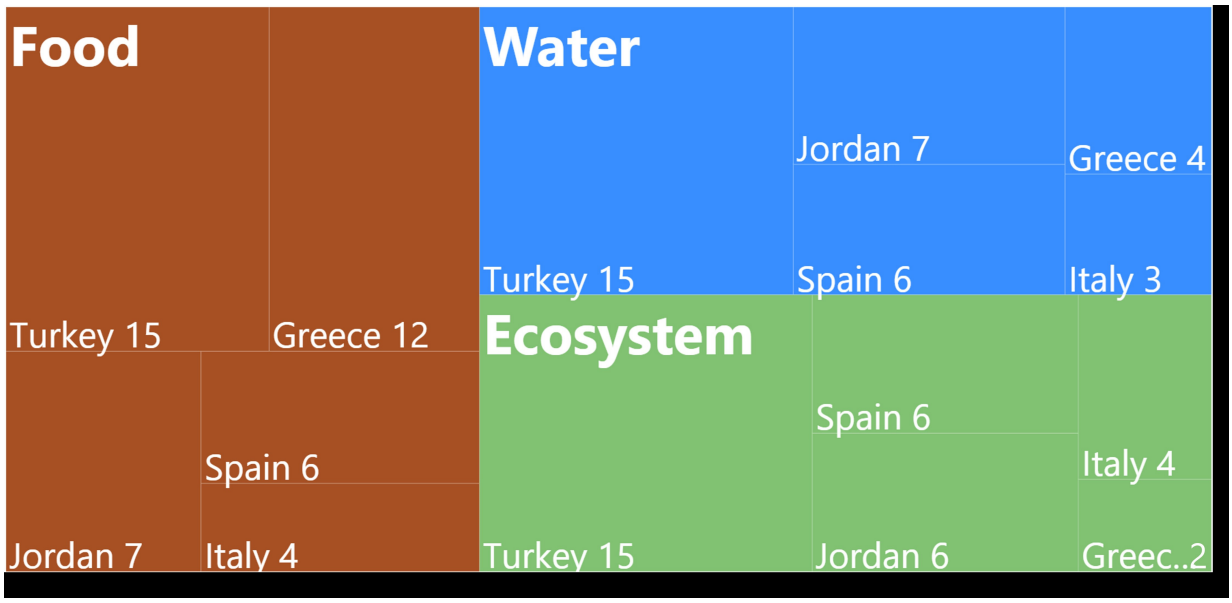


Figure 6. Initial group of stakeholders engaged for each Country grouped by Water–Ecosystem–Food sector. Labels indicate the number of stakeholders per country.

Table 3. Main challenges selected by stakeholders in the pilot areas, count: number of pilots whose stakeholders selected the challenge.

Main Challenges	Count
Improve the water resources management	4
Improve ecosystem services	3
Sustainable agricultural development	3
Preserve and develop/improve the ecosystem	2
Conserve, restore, and maintain ecosystems along with their services at a good status	1
Enhance the sustainability of the local development by reducing the environmental impacts of agricultural practices	1
Guarantee a sustainable high-value agricultural activity in the context of water scarcity exacerbated by climate change.	1
Maintain or increase agricultural production, while reducing agricultural costs	1
Minimise yield loss and preserve crop quality and quantity	1
Provide the farmers with a sustainable solution for the surging water prices	1
Reduction of the pressure on the water resources	1
Conservation and protection of natural space	1
Improve water quality and quantity with the enforcement of the annual water use plans	1

As shown in Table 3, 13 main challenges were selected by the different stakeholders of the pilot area. The main challenges identified are the need to "improve the water resources management", "improve the ecosystems services", and "promote sustainable agriculture development", selected by 66.6%, 50%, and 50% of the pilots, respectively. The pilot issues are evenly distributed between the three different WEF sectors (water, ecosystem, and food), as shown in Figure 7.

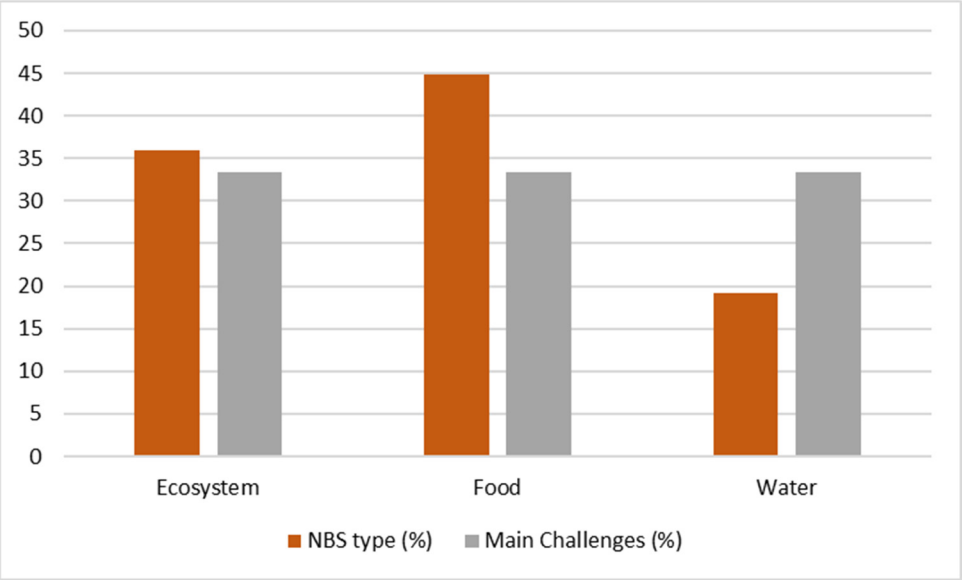


Figure 7. NBS types and main challenges defined by stakeholders in the pilot areas grouped by WEF aspects.

4.3. Nature-Based Solutions Selected by Stakeholders in Pilot Areas

In all the pilots, a list of 35 NBSs was selected, which were grouped into sub-types and Group types (Table 2). Sixty-two percent of identified NBSs are related to "Type 2—NBSs for sustainability and multifunctionality of managed ecosystems", 23% to "Type 3—Design and management of new ecosystems", and 15% to "Type 1—Better use of protected/natural ecosystems". As shown in Table 4, all stakeholders of the several pilot selected NBSs belonging to the sub-type "Agricultural landscape management" (61% of NBSs). The main NBSs selected are as follows: (i) Incorporating manure, compost, biosolids, or crop residues to enhance carbon storage (selected by all the pilots), (ii) Agro-ecological practices (iii) Increasing soil water holding capacity and infiltration rates, (iv) Soil improvement and conservation measures, (v) Mulching, (vi) Using soil conservation measures: Cover crops; Deep-rooted plants and minimum or conservation tillage; Agroforestry; Windbreaks.

Table 4. Numbers of NBSs selected by stakeholders grouped by sub-types per pilot area.

NBS Sub-Types	ES Donana	GR Koiliaris	GR Agia/Pinios Delta	IT Tarquinia	JO Deir Alla	TR Gediz
Agricultural landscape management	6	6	9	11	6	7
Coastal landscape management						1
Ecological restoration of degraded terrestrial ecosystems		5		4		
Monitoring				3		
Protection and conservation strategies in terrestrial, marine, and coastal areas ecosystems	1			4		3
Restoration and creation of semi-natural water bodies and hydrographic networks	4	2		2		
Total	11	13	9	24	6	11

4.4. NBSs Implemented in the Pilots

In four pilot areas, some NBSs were selected and implemented to solve some specific issues in different territories. Table 5 shows the types of NBSs experimented with in the pilot areas, the challenges individuated, and the benefits of implementing.

Table 5. NBSs implemented and their effect in summary.

Pilot Areas	NBSs Implemented	Outputs of the NBSs	References
Agia/Pinios Delta (GR)	Mulching/Mowing (Carbon addition)	Increasing Soil Organic Content; Increasing soil fertility.	[35]
	Efficient soil water management through irrigation scheduling	Water conservation (quantity and quality); Improved soil health and enhanced biodiversity; Reduced energy costs and increased farm profitability; Enhanced drought tolerance and adaptability to climate change.	[36]
Koiliaris (GR)	Agroecological practices (Carbon addition)	Improving soil aggregation and soil structure; Decreasing bulk density; Increasing soil porosity and the water-holding capacity; Improving soil fertility and soil biodiversity.	[37]
Deir Alla (JO)	No tillage	Increase water use efficiency (15%); Increase plant productivity (25%).	[38]
	Crop rotation with legumes	Increase water use efficiency (10%); Increase plant productivity (20%).	
	Incorporating organic manure	Increase water use efficiency (25%) and increase plant productivity (30%).	
	Crop Rotation	Increase water use efficiency (20%); Increase plant productivity (20%); Decrease the use of herbicide and insecticide (50%). Promotes the reproduction and activation of beneficial organisms and worms in the soil.	
Gediz Basin, Menemen Plain (TR)	Intercropping	Reduce the harmful effects of diseases and pests, prevents pollution, and results in effective use of resources.	
	Microbial fertilization	Microbial activity increases plant nutrient availability and soil fertility. Contributes to the protection of natural resources and sustainability in agriculture by improving soil quality.	
	Holistic regenerative practices	Reduce effects in the soil as a result of traditional agricultural habits such as soil pollution, degradation, salinity, etc.	

4.5. Stakeholders' Evaluation of NBS Implementation

The sample involved in the final survey comprised 18 respondents, selected on purpose among those more interested and/or directly involved in the implementation of NBSs: they were mainly researchers (44%), policymakers (28%), and farmers (22%) from Greece (33%), Spain (28%), and Jordan (22%).

Figure 8 shows the different characteristics of stakeholders and their main sector of interest in NBSs.

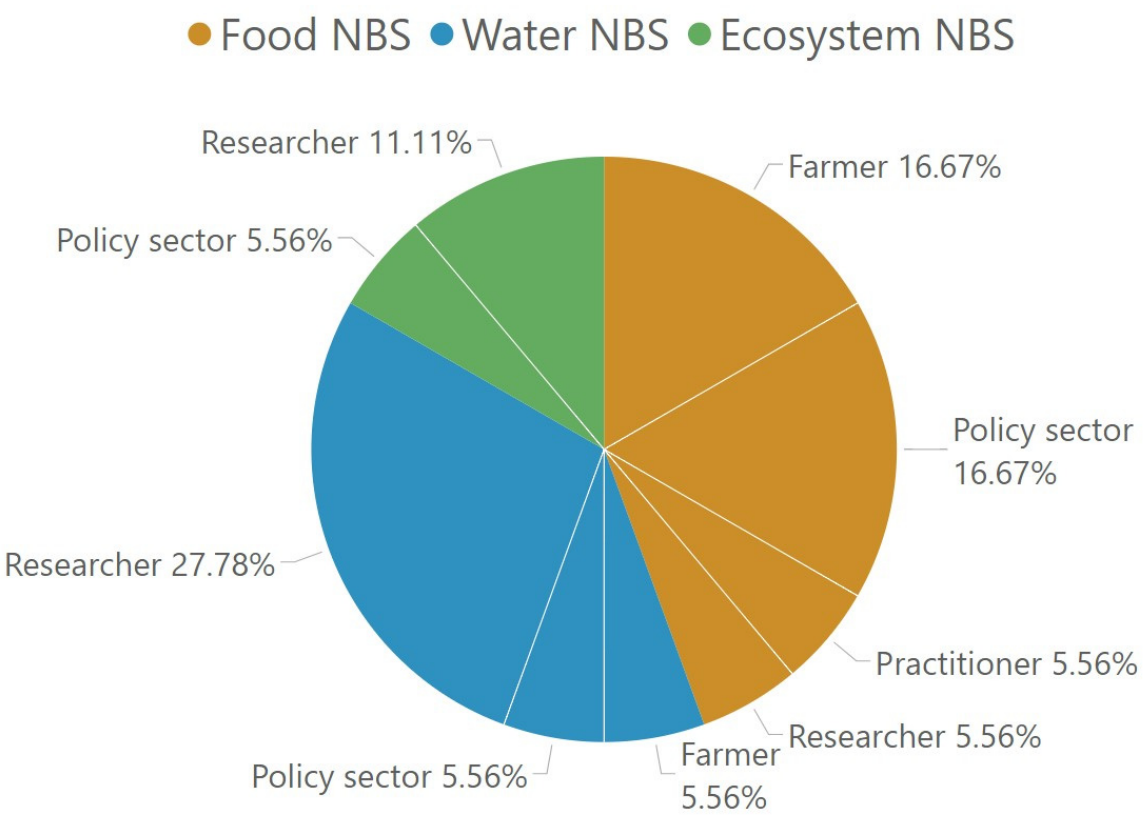


Figure 8. Stakeholder respondents grouped by WEF sectors.

Their role in the NBS implementation is shown in Figure 9: 28% of stakeholders support NBS in conceptual development (design) and/or coordination in the water sector, and 16% in the food sector; 22% of stakeholders did not implement NBS but are interested in the food sector, while the 22% of actors that supported practical NBS implementation are equally distributed in all WEF sectors.

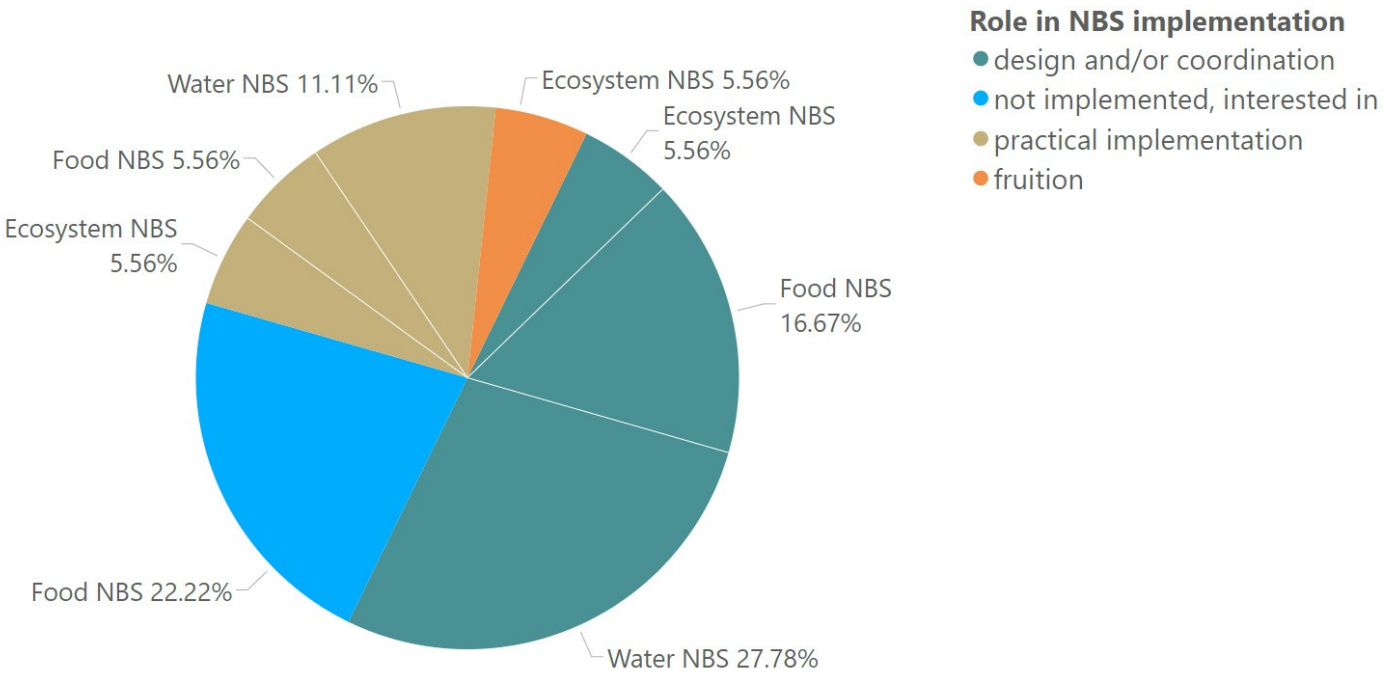


Figure 9. Role of stakeholders in implementing NBSs.

Figure 10 shows the results of the first Likert scale question regarding the level of satisfaction, ranging from 1 (very dissatisfied) to 7 (extremely satisfied), regarding "the level of community involvement in the planning and implementation of NBSs projects". Among the respondents, 44% (the majority) provided a response indicating neutrality (level 4), two respondents were extremely dissatisfied, and no respondents declared the highest level of satisfaction. The average score suggests that, in general, participants do not clearly identify NBS strategies as a valid and relevant approach to address specific environmental problems or issues but rather remain neutral. In addition, the lack of an extremely high score could indicate that some participants may have reservations or questions about NBS strategies.

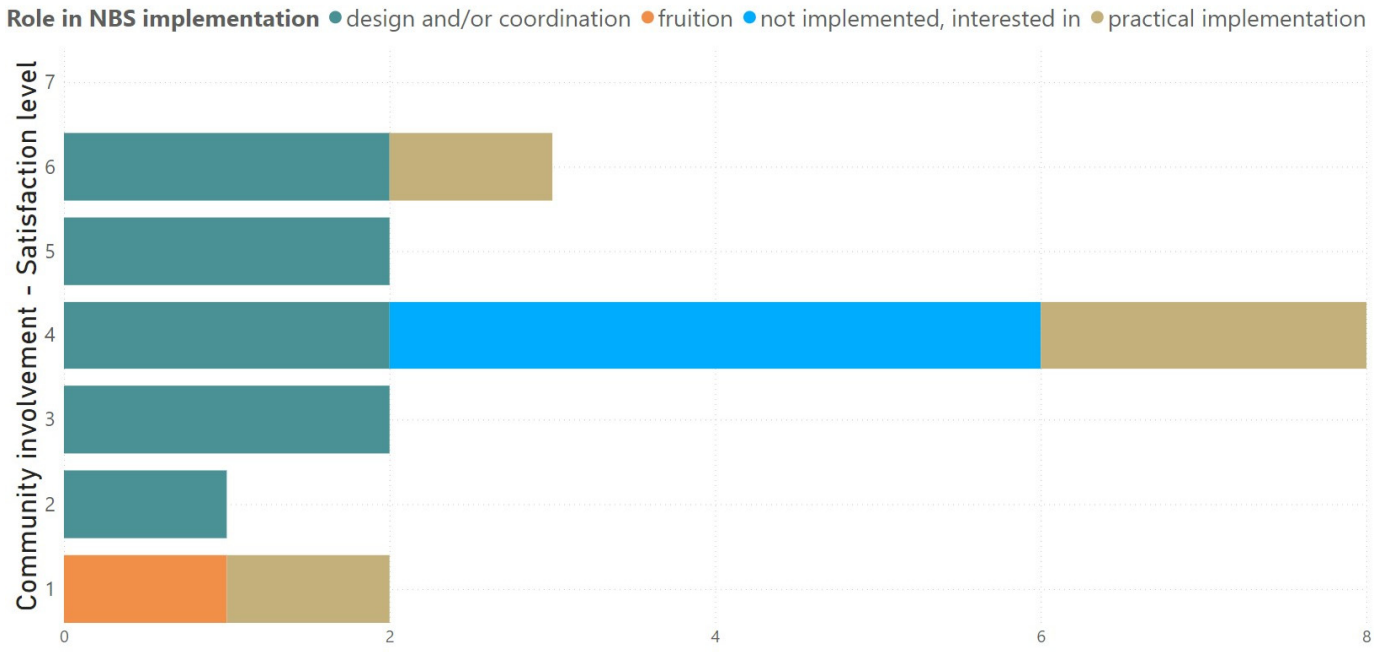


Figure 10. Responses about the level of community involvement in the planning and implementation of NBS projects in the different pilot areas (Ranging from 1—very dissatisfied to 7—extremely satisfied.

As shown in Figure 11, researchers are mainly satisfied with the NBS in the food sector, whereas farmers are satisfied with the NBS effect in the water sector.

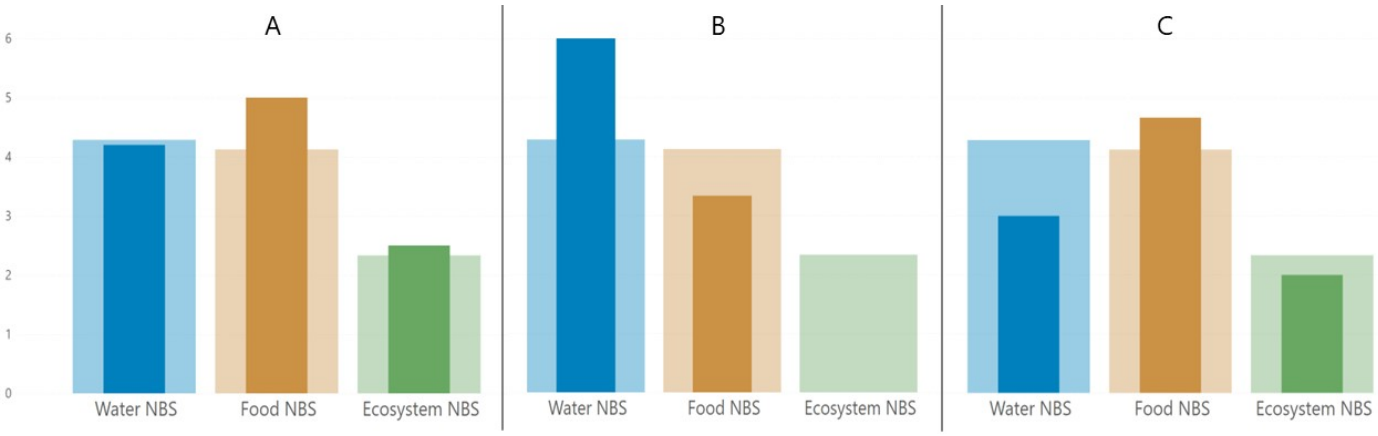


Figure 11. Community involvement—level of satisfaction (mean) per WEF sectors, highlighted in darker colours: researchers' (**A**), farmers' (**B**), and policymakers' (**C**) satisfaction against the total.

Figure 12 describes the agreement of each participant on the effects of NBS implementation: the different questions were tailored to the WEF-specific section of NBSs. All

respondents who have implemented NBSs in the different WEF sectors provided responses indicating a high level of agreement, ranging from 4 to 7 on the Likert scale.

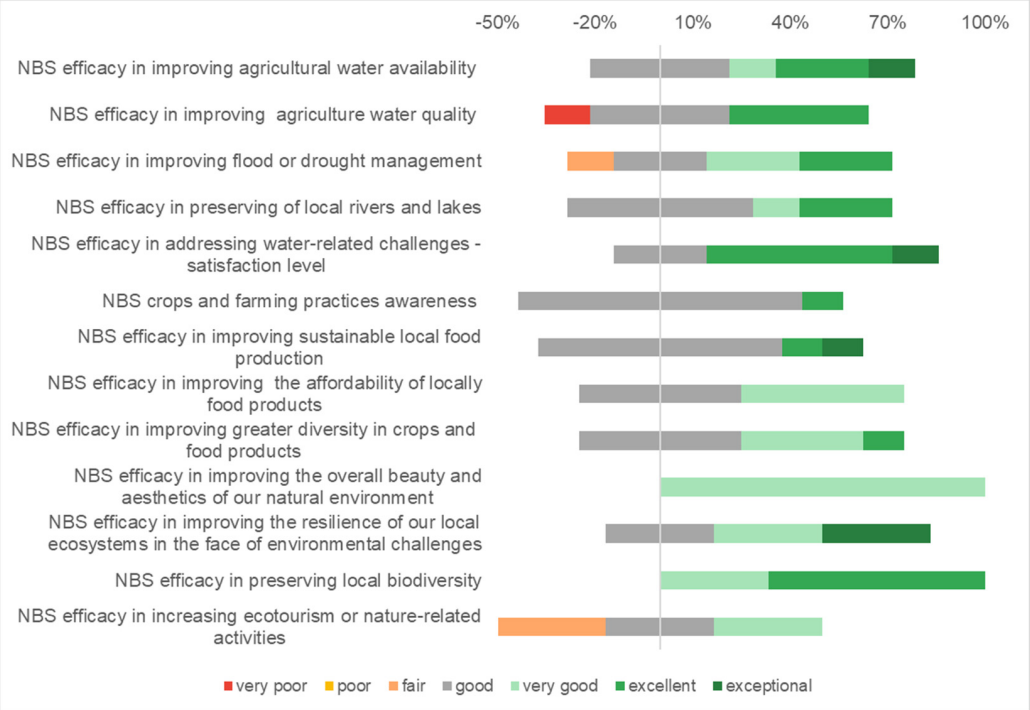


Figure 12. Percentage of agreement related to NBS efficacy in providing different services for the water, food, and environment sectors, as identified by stakeholders in the 6 countries involved in the consultation campaign.

Some stakeholders did not perceive any positive effects from the use of NBSs in improving water quality in their community; 14% reported even a very negative effect, as well as in managing floods or droughts. With regard to the ecosystem sectors, the majority of stakeholders did not perceive a very positive effect on the increase in ecotourism or nature-related activities.

4.6. Barriers and Opportunities Affecting NBS Implementation

Stakeholders have the option to select multiple choices from a range of 10 barriers and 10 opportunities to overcome barriers. The first two barriers that hinder the successful implementation of the NBSs, as indicated by the respondents, are related to economic aspects: 'Economic constraints' and 'Yield and profits may not respond as farmers' expectations' were the most voted, with 50% of preferences. The other two important barriers (44.4% of preferences) are 'Few communications and limited awareness of the importance of NBSs in society' and 'Lack of good policies and incentives' (Figure 13).

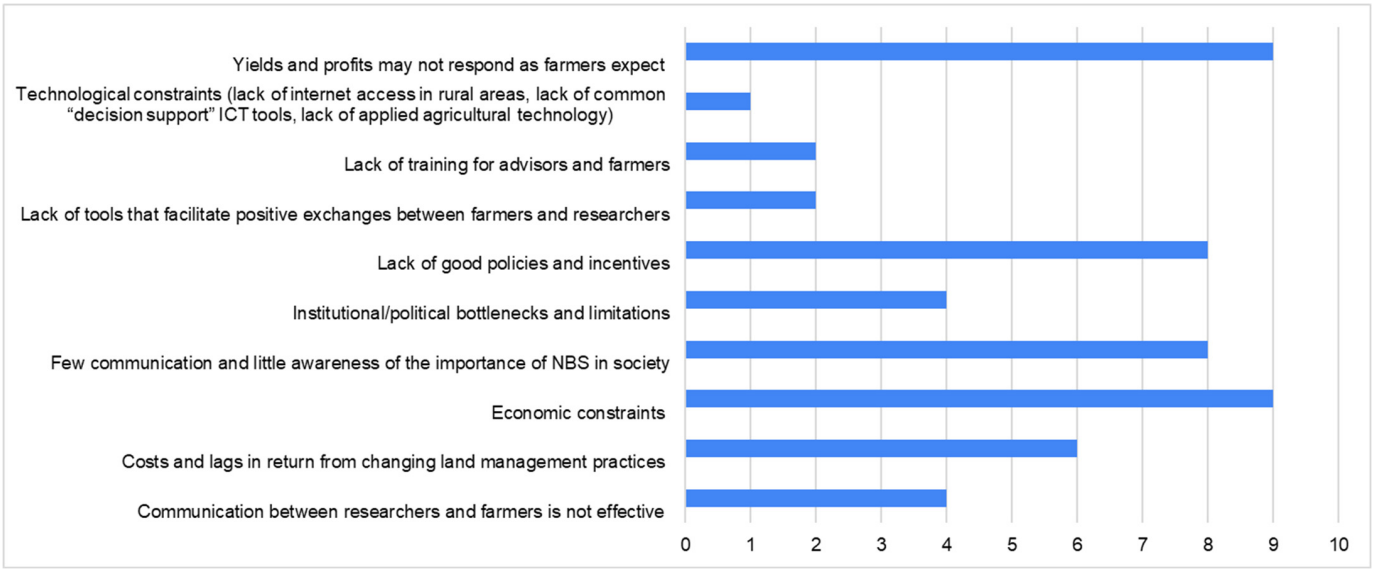


Figure 13. Barriers related to NBSs identified by stakeholders in the 6 countries involved in the consultation campaign (numbers correspond to count of responses).

The three main opportunities to overcome the issues of implementing NBSs are 'Financial support for investments in NBSs', 'Good policies and incentives with effective policy measures', and 'Policymaking and legislation to support the implementation of NBS practices', with 78%, 61%, and 50% of preferences, respectively (Figure 14).



Figure 14. Opportunities related to NBSs identified by stakeholders in the 6 countries involved in the consultation campaign (numbers correspond to the count of responses).

5. Discussion

This study aims to identify the potential role of NBSs in addressing the challenges and opportunities for a resilient Nexus in rural areas, building on the challenges identified within the pilots through a participatory approach and implementing selected NBS that can contribute to climate resilience by improving the adaptability of ecosystems to changing climatic conditions. This study shows the methodology that was followed for the implementation of the catalogue, holding a list of existing nature-based solutions (NBSs) specific to rural landscapes and making them available to the wider public. The NBS catalogue contains a total amount of 54 NBSs, along with additional information for each one of them. While there is growing evidence based on the effectiveness of NBS approaches [16] and increasing numbers of tools to support practitioners [39,40] and policymakers in planning and applying NBSs, some important gaps remain, including matching solutions to specific circumstances and stakeholder needs. This study will address this gap by providing the methodological and practical foundations for the selection of suites of solutions that use NBSs as an underlying principle to be implemented in Mediterranean pilot areas. The NBS Catalogue was developed to give decision-makers access to an evidence-based framework

and guidance to support the selection of suites of solutions that incorporate nature-based approaches to address challenges in increasing the resilience of the WEF Nexus.

Summarizing the information resulting from the application of the WEF Nexus Evaluation framework, the vision of all pilots is common and threefold: (i) Increasing sustainability and re-naturalization of the landscape; (ii) Focusing on the sustainability of the agricultural sector; and (iii) Promoting the socio-economic development. The optimization of the WEF Nexus is a core issue for the sustainable management of natural resources and agricultural development. NBSs can play a key role in facilitating this optimization.

Agricultural landscape management NBS types are more selected by the several stakeholders of the Mediterranean pilot areas to overcome the main WEF challenges of their areas. Also, Morri and Santolini [41] highlighted that agricultural management practices are key to realizing the benefits associated with ESs and reducing disservices from agricultural activities in an Italian region.

The survey on the impact of NBS implementation had a limited response rate (18 respondents). However, it was targeted at stakeholders who had implemented NBSs in their area, making it an excellent proof of concept. According to the results, although similar to Seddon et al. [16], there was a generally positive perception of the effectiveness of NBSs in the WEF sectors, but stakeholders did not perceive a positive impact of the application of NBSs in improving water quality in the pilot areas. This is probably due to the very short-term implementation of NBSs: sustainable NBSs need time to show effects on the water quality. Several studies [42,43] highlighted that NBSs can positively impact surface water quality in the long term and will remain an effective strategy in the future, even under future climate conditions, while being a justified investment from an economic standpoint.

The stakeholders' consensus regarding the effectiveness of the adopted strategies is a pivotal finding, indicating the success of the NBS initiatives within their respective communities. It suggests that the strategies have effectively addressed key challenges related to water availability, food security, and ecosystem resilience, contributing to sustainable agricultural practices and environmental conservation efforts.

In addition to defining an NBS list tailored to specific territorial issues, it is important to establish the barriers that arise in implementing practices to seek useful needed actions. In this context, our study defined the main barriers in Mediterranean regions in the phase of NBS implementation through a participatory approach. Economic and social barriers are highlighted by stakeholders as a priority. As described by Hallstein and Iseman [44], any practice that reduces returns or is perceived to reduce returns will face high resistance to adoption. In many cases, simply the lack of concrete and specific evidence on yields and subsequent returns will prevent the adoption of new practices. Several studies in the NBS application indicate that farmers do not adopt sustainable practices despite having witnessed ecosystem benefits because of increased initial costs, labour inputs, or customs and preferences [45–47]. To maximize NBS benefits while managing trade-offs, Seddon et al. [16] identified support for NBS in government policies, participatory delivery involving all stakeholders, strong and transparent governance, and provision of secure finance and land tenure, which are in line with international guidelines.

In the same perspective, our study moves in the same direction as the cited literature and provides evidence that financial support, sound policies, and incentives, particularly those aligned to the CAP, are crucial to pose the base for implementing NBSs at the territorial level.

As confirmed by several authors [48,49], legislative and financial support for NBSs cuts across several policy documents and sectors. While Member State and EU policy instruments acknowledge NBS-related concepts, they seldom contain quantitative and measurable targets relating to NBS placement and quality. NBSs, therefore, provide an important opportunity for innovation, research, business development, and trade [11].

Due to project time constraints, this paper shows only the first results of the implementation of NBSs, and future studies on the current topic are therefore recommended for the monitoring of NBS effects on WEF sectors.

6. Conclusions

Methodologies and evaluation frameworks for assessing the effectiveness and impact of NBSs are still insufficiently understood, as is the implementation of NBSs and the relationship between NBSs and society, especially in rural areas. The present research aimed to develop a stepwise methodology to find the most appropriate NBSs to implement in WEF sectors in rural areas. In order to legitimize new planning practices and concepts, participatory methodologies were used to establish collaborative networks and communities of practice across institutional boundaries. An NBS catalogue has been prepared and is publicly available on the LENSES project website. Stakeholders identified the main local WEF challenges and selected a list of NBSs to be evaluated in light of the local context. In four pilot areas, a few NBSs were implemented, and the first positive results were presented. A final survey was conducted as proof of concept to highlight the main barriers and opportunities of the NBS implementation. Although the final investigation is based on a small sample of participants, the findings suggest that NBSs have been recognized as a promising and sustainable approach to addressing various environmental challenges, including water and food-related issues, and that economic and social barriers are the main issues in implementing NBSs. The success of NBSs in Mediterranean areas would also depend on effective governance, policies, and the integration of traditional knowledge with modern approaches to improve the perception and attitude of stakeholders. This study, through a small set of implemented NBSs in some case studies, provides evidence that the knowledge gained through experiences in NBS implementation and information sharing between stakeholders can be an opportunity to facilitate NBS actions. Finally, it is crucial to continually assess and adapt these solutions based on monitoring and evaluation. Further research is also needed to determine the impact of implementing NBSs over the long term and for tailoring NBSs to specific contexts, including the geographical, climatic, and socio-economic conditions of a region.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16104064/s1, LENSES NBSs assessment Questionnaire.

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