microplastics

Article

Crafting a Scientific Framework to Mitigate Microplastic Impact on Ecosystems

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Abstract: Microplastics (MPs), microscopic particles originating from plastic products, have emerged as a persistent environmental challenge, posing threats to both ecosystems and human health. Their omnipresence, extending from the highest mountains to the deepest oceans and infiltrating the bodies of humans and animals, requires urgent attention. In the face of escalating annual plastic production and inefficient waste management, where 79% of plastic production ends up in landfill sites or enters the environment, MPs multiply as its consequence. This emphasizes the urgent need for a comprehensive global framework that transcends borders to systematically address and control the growth of MPs. In response, our research conducts an in-depth investigation and proposes a seven-step strategy, providing a global perspective for mitigating microplastic pollution. The proposed approach begins with initial research steps and closes in predicting the remediation of areas impacted by microplastic pollution.

Keywords: mitigation strategies; human health; circular economy; policy and regulation; global scale

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1. Introduction

Microplastics (MPs) are polymers and plastic-origin particles measuring less than 5 mm. They result from the breakdown of larger fragments through mechanical or physico-chemical processes, or the intentional engineering of materials, and include micro particles of a size less than 1 mm and nano particles smaller than 1 micrometer. The diverse origins of MPs contribute to their variations in hardness, softness, and structural regularity or irregularity. Due to their small size, MPs possess a significantly larger surface area, facilitating the adsorption of a wide range of pollutants on their often-hydrophobic surfaces. These tiny particles enter diverse environmental compartments, from rivers and soils to the atmosphere, and from the deepest depths of the oceans to the most remote areas of the polar regions [1–6].

Between 2020 and 2023, there was a notable increase in published articles examining the adverse effects of MPs on ecosystems, food chains and human health [7–12]. This growing attention to the topic has sparked widespread discussions across various communities. Several research articles have explored the interaction between MPs and the human body, addressing health concerns related to the topic. For instance, research has revealed the presence of MPs in human blood [13] and baby placenta [14], emphasizing the urgency to investigate their potential impacts on sensitive human organs, including the brain and heart [15,16]. Furthermore, studies have examined their influence on neurological behavior [17], the immune system [18,19] and disruption in gene transcription [20]. These findings, while significant, only scratch the surface, and a deeper exploration of this subject reveals the remarkable ability of MPs to adsorb various pollutants, acting as carriers into the human body and other living organisms [21,22].

Scientific studies have explored the widespread distribution of MPs in water, atmosphere, and soil, aiming to understand their complex physical, chemical, and biological impacts on ecosystems. The presence of MPs in water supplies, as demonstrated by various studies, is a direct consequence of inadequate control of the MPs release into surface waters [23,24]. Urban or industrial wastewater treatment facilities have been identified in several studies as significant contributors to this issue [25–27]. These facilities are also recognized as a major source of MPs in soil through wastewater sludge and irrigation, alongside with other contributors such as atmospheric transport deposition [3,7,28,29].

Further studies emphasize the long-term physicochemical effects of microplastic pollution on factors such as acidification, and water quality indicators such as turbidity, suspended solids, or water temperature [30,31]. Additionally, research indicates the adverse impacts of MPs on a variety of aquatic organisms, ranging from small organisms to larger marine life [32–34].

To effectively address the ongoing challenge of microplastic pollution in a sustainable way, a comprehensive approach that incorporates environmental, social, and economic considerations is essential [35]. The MPs–sustainability nexus represents a complex interconnection of essential factors, critical for the sustainable management and mitigation of the environmental impact of MPs. Despite the importance of the topic, it has not yet been studied systematically and comprehensively within a structured framework.

In this article, we investigate the components of mitigating the environmental impact of MPs, leveraging our own insights, research, and data analysis as well as insights gleaned from recent published articles, case studies, and examples from relevant studies. We explore the key factors influencing this field and discuss how each contributes to the development of a sustainable strategy to combat microplastic pollution. Our aim is to provide insights into the comprehensive approaches required for the effective management and mitigation of the adverse effects of MPs on a global scale. The outlined plan of action is designed to assist professionals and decision-makers engaged in this field.

2. Comprehensive Framework for Microplastic Mitigation

Figure 1 provides an illustration of the remarkable increase in global plastic production, reaching a notable 400.7 million metric tons (Mt) in 2022 and expected to rise to 753 Mt by 2060. The graph was generated using Origin data analysis version 2018 software, incorporating data available up to 2022 from [36,37], and employs interpolation and extrapolation techniques to bridge data gaps and extend projections until 2060. The observed escalation in plastic production, as indicated by the graph, underscores the parallel rise in microplastic production. As plastics continue to be the primary source of MPs in the environment, understanding the dynamics of plastic production is crucial for recognizing and addressing the broader implications of microplastic pollution.

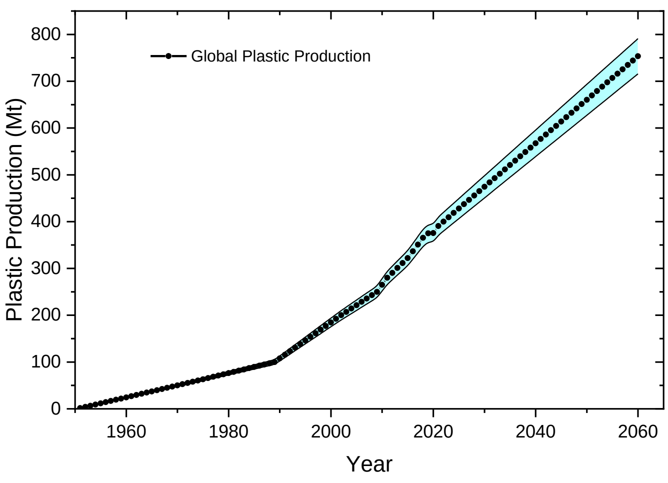

Figure 1. Global Plastic Production from 1951 to 2060, with standard error. The graph was constructed using data up to 2022 [36,37]. Data analysis techniques were employed to extend the projection until 2060, with the standard error shading representing the associated uncertainty.

In Figure 2, the timeline graph illustrates the global production and projected trend of MPs from 1951 to 2060. Graph A of Figure 2 shows a significant increase from 3.6 Mt in 2023 to 7 Mt in 2060, indicating an 84.2% growth. The data for microplastic production values for this graph were derived from [38,39], based on 2015 statistics relevant to the initial release of MPs into the environment from production to their end-of-life, and applied data from Figure 1. The cumulative graph in Figure 2B further reveals that the total volume of MPs released into the environment amounted to approximately 96 Mt in 2023, with projections foreseeing an escalation to near 298 Mt by 2060. This highlights the pressing need for establishing a comprehensive framework to address this issue.

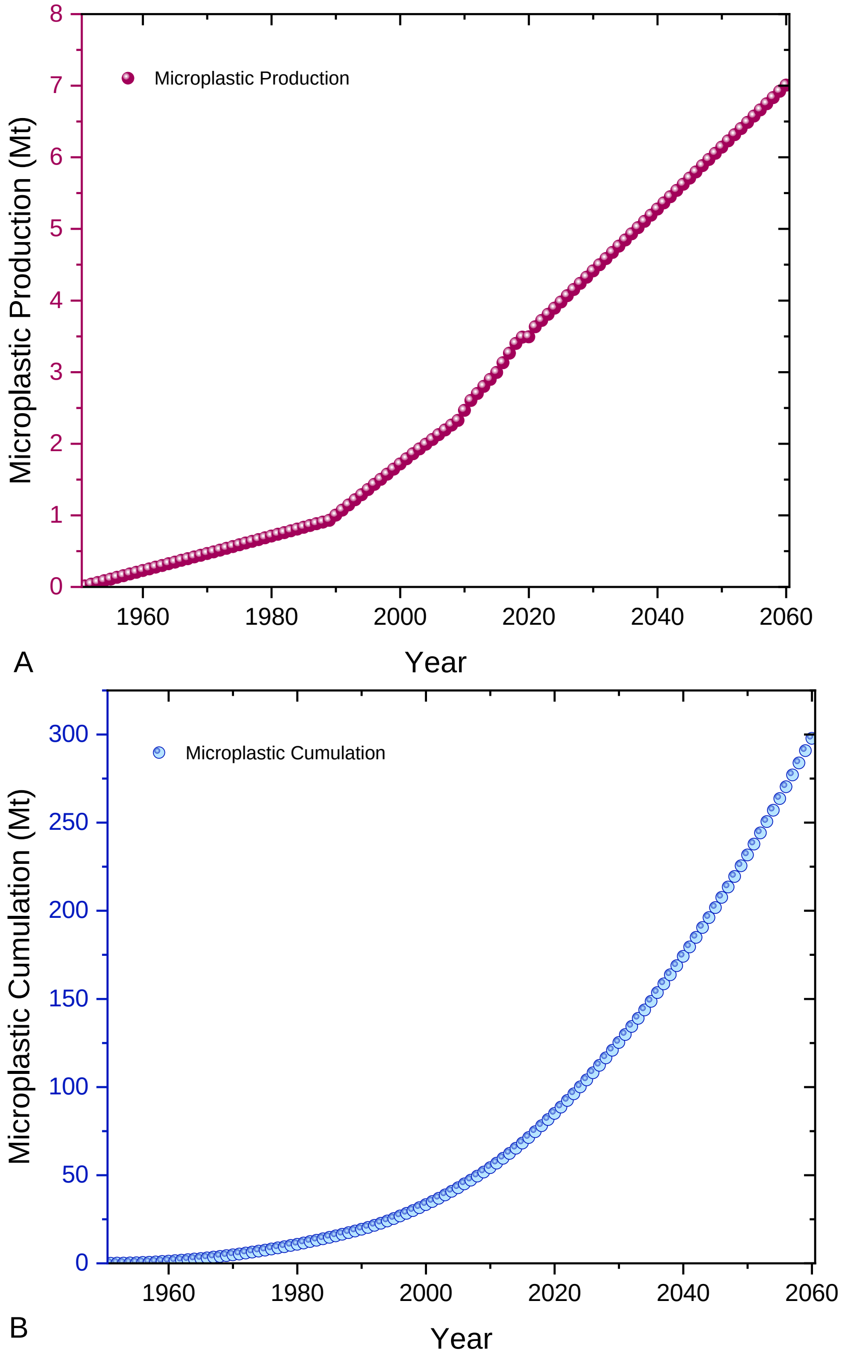

Figure 2. Timeline graph illustrating (**A**) the global production and projected trend of microplastics and (**B**) their cumulative impact from 1951 to 2060, using data from global plastic production (Figure 1) and microplastic production data from [38].

Addressing the impact of microplastic pollution on ecosystems requires a detailed framework that considers key aspects of microplastic identification, control, and monitoring. The integration of legal considerations plays a crucial role, ensuring commitment to policies and regulations governing plastic production, use, and disposal. Our objective is to incorporate all factors reasonable to microplastic mitigation. This comprehensive approach requires the complex interplay of various elements, including research and monitoring, waste management and recycling, circular economy principles, policy and regulation, education and awareness, industry collaboration and innovation, and ecological restoration. In subsequent sections, we will undertake an in-depth exploration of each factor and discuss its specific influence on the dynamics of microplastic pollution.

2.1. Research and Monitoring

Microplastic represent a growing concern and need a robust framework of research and monitoring to comprehend their environmental, biological, and human health impacts. In recent years, a considerable amount of research has been dedicated to developing analytical methods, an ongoing initiative crucial for effective monitoring. The dimensions (size) of micro and nano MPs, and their diverse sources and types, present some of the most challenging questions that must be addressed during the analysis process [40]. The widespread distribution of MPs in the environment creates major challenges for monitoring efforts [41]. A potential solution lies in integrating monitoring into routine tests across diverse laboratories related to water, wastewater, soil, air, and health, which emerges as a more effective approach to address this issue. The subsequent sections highlight the ongoing interconnections in microplastic research and monitoring.

This section emphasizes the significance of persistent research efforts and the crucial need for standardized monitoring procedures to address the challenges of microplastics comprehensively.

2.1.1. The Importance of Ongoing Research

The presence of MPs across diverse ecosystems requires ongoing research to accurately estimate their abundance and distribution. Research initiatives dig into oceans, rivers, soils, and even the atmosphere to investigate the scope of contamination and pinpoint hotspots. Hence, understanding the extent of MPs is fundamental for designing effective mitigation strategies (see Figure 2).

Another important aspect relates to the release of MPs from various sources, categorized as primary, e.g., microbeads in personal care products, and secondary, e.g., microfibers from textiles. Ongoing research efforts try to explain these sources and trace the pathways through which MPs infiltrate the environment. Identifying these origins is crucial in creating targeted prevention methods.

Figure 3 illustrates the global fiber production distribution across natural, semi-synthetic, and synthetic categories [42]. The pie charts within each fiber group display the associated products and their respective percentages, revealing that polyester alone accounts for 54% of the total global fiber production within the synthetic category. Additionally, a test was conducted to observe the effects of the washing process on synthetic silk threads using brand new yarn. The microscopic image of the results is depicted within Figure 3. Upon mechanical washing and interaction with detergent, microfibers with diameters less than 10 microns became damaged and detached from the twisted structure of the thread. The washing machine mechanism releases a significant number of particles, ranging from 220,000 to 2,820,000 microfibers per kilogram of textile [43]. A study indicates that around 76% of MPs are captured and transferred to sludge in wastewater treatment plants (WWTPs), reaching approximately 46 particles/g, with 89.5% of these particles comprising synthetic polymers such as polyesters, polyamides, polyethylene terephthalate, and polyethylene [44]. In addition to the retention and transfer of MPs in WWTPs, microfibers can also enter the environment through alternative pathways such as landfill sites or directly from yarn fibers. The subsequent dispersion of these particles into the atmosphere from contaminated areas plays a significant role in the widespread dispersion of microfibers across ecosystems [45].

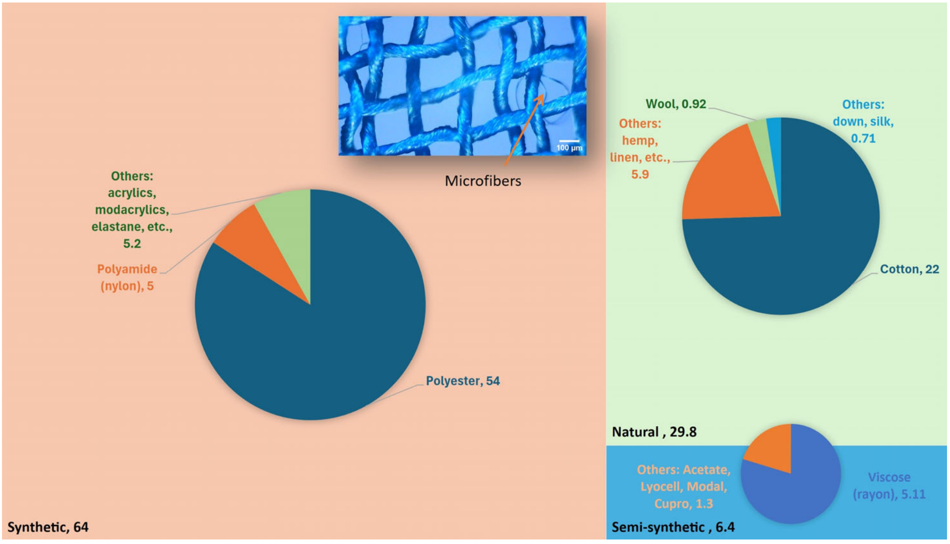

Figure 3. Treemap illustrating global fiber production in 2021, categorizing natural, semi-synthetic, and synthetic fibers with data sourced from [42]. The pie charts within each fiber group show the associated products within their respective category. The microscopic image of a synthetic yarn demonstrates the effects of the washing process on silk threads and the separation of microfibers from the thread during the process.

Experimental investigations play a crucial role in understanding the ecological impacts of MPs on aquatic and terrestrial life. Assessing the impact of MPs at different trophic levels, from marine organisms to wildlife on land, helps to explain the cascading effects in the ecosystem [46–48]. Furthermore, an in-depth understanding of the potential health effects of MPs on humans is a crucial aspect of ongoing research, addressing the concerns arising from their persistent presence in water, the food chain, and the atmosphere [49,50]. Significantly, the latter are still relatively unexplored, possibly due to strict laws and restrictions for direct human experimentation, while there is an urgent need for in-depth studies on the effects of MPs on sensitive organs. These studies should go beyond conventional tests with pure polymers and include scenarios with contaminated MPs, highlighting their potential impact on human health.

2.1.2. Standardized Monitoring Protocols

One of the most problematic issues related to MPs is the lack of reliable data. To effectively track and compare microplastic levels and trends on a global scale, standardized monitoring protocols are essential. Various techniques, including visual inspection, spectroscopic methods, microscopy imaging, filtration, and gas chromatography, are considered crucial for quantifying microplastics. These methods partially address microplastic analysis and vary in complexity, cost, and suitability, depending on sample characteristics and research goals. Therefore, a combination of these techniques is often necessary to obtain accurate and comprehensive data on microplastic pollution across diverse environmental compartments. Lessons learned from case studies conducted across different regions, addressing challenges, comparing results, and evaluating the degree of success, collectively represent the most effective strategy for initiating standardized methodologies in MPs research [51–54].

Employing reliable methods for sampling, processing, and analyzing confirms the uniformity of the data and enables meaningful comparisons between regions and over time. This standardization is essential in generating accurate measurements of the microplastic distribution. It is crucial for these standards to applied globally rather than locally, since global approach is addressing the migration process of particles within the ecosystem via water and atmospheric currents, thereby facilitate the tracking of MPs.

Through the careful application of proven methods, the investigation of MPs offers various advantages, both in the short and long term. In the short term, monitoring provides timely insights into immediate environmental impacts, aiding rapid response strategies. Long-term monitoring, on the other hand, enables the detection of trends and cumulative effects by using standardized protocols and provides a comprehensive understanding of microplastic dynamics over longer time periods [55]. Conducting regular assessments at specific time intervals helps to identify deviations, evaluate the effectiveness of intervention measures, and adapt strategies to effectively mitigate the problem. Integrating AI and global network platforms is a promising way to support both research institutions and governments in accessing first-hand data for microplastic dynamics [56,57].

Standardized monitoring protocols should follow a multi-sectoral approach that considers oceans, freshwater bodies, soils, sediments, and air. Such integration enables a comprehensive understanding of the links between these sections within the microplastic cycle and allows for universal assessment and focused action.

2.2. Waste Management and Recycling

In addressing the escalating microplastic pollution (see Figure 2), crucial waste management practices and effective recycling initiatives are of utmost importance. In 2022, the global production of recycled plastic accounted for approximately 9% of total plastic production. Consequently, about 19% of produced plastics were incinerated, nearly 50% ended up in sanitary landfills, and the remaining 22% were improperly disposed of, thus entering the environment as a source of MPs [58].

In this context, the term "waste" covers all categories that can produce MPs, while recycling is the countermeasure that utilizes waste to create new life cycles and prevent microplastic pollution. This section explains the crucial role of effective waste management systems in preventing the release of MPs into the environment.

2.2.1. Effective Waste Management

The journey of plastics from production to eventual fragmentation starts with physical and mechanical degradation processes, intensified by improper collection and inadequate disposal practices. Effective waste management emerges as a crucial barrier against microplastic leakage into the environment. This includes the use of secured landfills to prevent their dispersion into the atmosphere, surrounding soil, and water resources. Additionally, alternative approaches to traditional waste disposal methods, such as incineration or pyrolysis initiatives, offer additional options for managing plastic waste.

Effective waste management is a comprehensive approach that includes planning, infrastructure development, education and the active involvement of communities and industry to minimize the environmental impact of waste. However, effective waste management practices are not yet in place in many regions, meaning that plastics can remain in the environment for long periods of time, leading to increased breakage and the subsequent release of MPs [59,60].

2.2.2. Recycling as a Mitigation Strategy

The promotion of recycling is an effective strategy to mitigate microplastic pollution. Recycling involves reprocessing plastics into new products, reducing the need for virgin plastic production. However, it is critical to note that the recycling process itself, if not executed with precision, can contribute to the production of MPs. Routine recycling processes, such as washing, mechanical shredding, and the production of granular particles, can lead to the fragmentation of larger plastics into smaller particles, ultimately contributing to the generation of MPs. Inadequate filtration during the recycling process allows a considerable proportion of particles smaller than 5 microns to escape, elevating the probability of plastic waste fragmenting into MPs [61,62]. Innovation and advancements in recycling technologies are essential to enhance efficiency, minimize particle escape, and ultimately contribute to a significant reduction in microplastic pollution.

2.2.3. Reducing Plastic Waste

Directly addressing the issue at its source, i.e., reducing plastic waste, is a powerful and impactful approach to mitigate microplastic pollution. This comprehensive strategy starts at the community and industrial levels, supported by government policies aimed at eliminating the excessive use of plastic through legislation and financial investments. A notable case study from Australia highlights the impact of well-designed waste management programs. The communities with illegal dumping initiatives, litter prevention strategies, and recycling programs showed significantly less waste along their coasts compared to those without such comprehensive programs [63].

However, resistance from industry sectors and logistical challenges pose significant barriers to the implementation of plastic waste reduction strategies. This resistance can arise from concerns over increased operational costs or the potential impact on profitability. Additionally, logistical barriers stem from the complexity of implementing changes to existing infrastructure and supply chains. Overcoming these challenges often requires a significant investment of time and resources. Nonetheless, the outcomes of a well-defined strategy aimed at reducing the overall volume of plastic waste generated will reduce the potential for MPs to penetrate ecosystems [64].

2.3. Circular Economy

Microplastic pollution is tightly linked to the linear model or inadequately designed circular models of production and consumption, where resources are extracted, used, and then discarded, resulting in extensive waste and environmental damage. As highlighted in Section 2.2, a significant 79% of all produced plastic either ends up in landfill sites or enters the environment, leading to the extensive and continuous release of microplastics into the environment [65]. This section explains the principles of the circular economy and its application to the plastic life cycle, outlining effective strategies to reduce the release of MPs into the environment.

2.3.1. Circular Economy Principles

The circular economy promotes a regenerative approach wherein materials and products are kept in a continuous loop to maximize their value and minimize environmental harm, which opposes the traditional linear “take-make-dispose” model [66]. The 4R initiatives “Reduce, Reuse, Recycle, and Recover” form a crucial framework for sustainable plastic management. The initial and essential step involves reducing plastic consumption at the source.

Enhancing the quality of products and encouraging their prolonged use within the cycle as original goods is essential. This also involves using less plastic, prioritizing the potential use of recycled plastics, and exploring alternative materials such as glass and wood, especially when sourced from recycled rather than raw materials. In the case of applying recycled plastics, it is crucial to ensure that the quality of the materials is not compromised, so that the same standard as the original is maintained and the generation of additional MPs is avoided. The reuse of products or materials reduces the need to produce new plastics. If the products remain undamaged or do not contribute to the formation of MPs due to their age, they can be used by customers over a longer period and, thus, remain in the value chain [67]. Nonetheless, careful consideration is needed to ensure that the designed model of circular economy practices does not unintentionally increase microplastic generation or pose additional harm to the environment.

The concept of Extended Producer Responsibility (EPR) traditionally revolved around producers taking responsibility for the entire life cycle of their products, including proper disposal and recycling. However, it is important to emphasize that EPR should evolve to include a broader environmental perspective. In particular, the issue of microplastic production should be clearly integrated into EPR frameworks. By doing so, manufacturers would not only be motivated to design products with a focus on recyclability and sustainability but also to actively minimize the generation of MPs throughout the product life cycle. This adaptation would align EPR with existing environmental concerns, particularly the adverse effects of MPs, and provide robust motivation for producers to contribute to the reduction of MPs in the environment [68,69].

2.3.2. Application to Plastic Life Cycle

The shift toward a circular economy for plastics represents a substantial transformation that requires collaboration between stakeholders, innovative technologies, and a shared commitment to sustainability. Life Cycle Assessment (LCA) is a powerful tool for industries to facilitate understanding and characterization of the range and scope of environmental impacts, e.g., resource use, human health, and ecological consequences, from raw material to production use and disposal, covering all stages of its life [70,71]. Besides, LCA, when applied to plastic life cycle analysis, includes aspects like energy consumption, greenhouse gas emissions, and waste generation. Incorporating the assessment of MPs in biota and other ecosystem components, such as soil and air, into the LCA framework is essential for a comprehensive understanding of the environmental impact of MPs. By considering the implications of MPs on different components of the ecosystem, LCA becomes a comprehensive tool to evaluate the genuine environmental consequences of plastic pollution [72,73].

Figure 4 illustrates the LCA of microplastic release during the production of car tires. This release begins with industrial emissions from the processing of raw materials, primarily revealed as MPs in wastewater. This release continues throughout the tire's lifetime, with tire wear being a significant contributor to atmospheric pollution, accounting for up to 11% of PM10 levels [74]. Additionally, tire wear contributes to road runoff, ranging from 5 to 92 mg/g dry weight, and deposits MPs in the soil at levels of 0.2 to about 160 mg/g. Studies have measured tire wear per capita in various countries, reporting masses ranging from 0.2 to 4.7 kg/(cap*a) with a global average of 0.81 kg/year, and an estimated relative contribution to the total global plastic in oceans ranging from 5% to 10% [75].

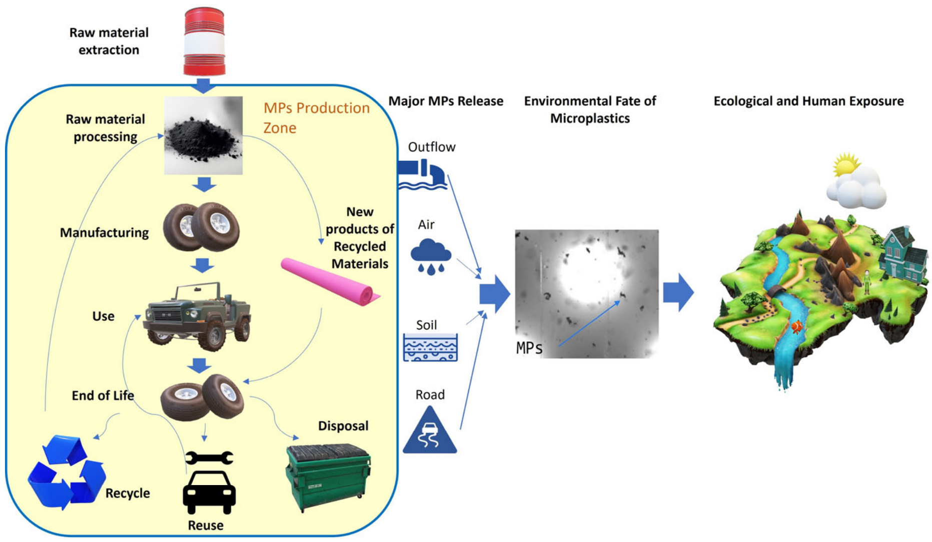

Figure 4. LCA framework for car tire production and microplastic release in real-world scenarios. The yellow box represents the stage where MPs are actively produced and subsequently released through major pathways.

Post-use scenarios, including tire repair and reuse, introduce additional ways for microplastic release. Recycling, as another end-of-life option, involves multiple stages such as transportation, leachate production, and final product manufacturing, all of which contribute to microplastic emissions. The quality of the final recycled products and the degree of particle integration are critical considerations in managing microplastic release. The selected recycling method also plays a crucial role in this process.

Disposal methods pose significant challenges in the context of microplastic pollution. Open dumping sites release MPs into the atmosphere and water, leading to soil pollution. In the case of landfilling, leachate continues to contribute to the contamination of ecosystems by releasing MPs, particularly in unprotected sites or when subjected to inefficient leachate treatment in secured landfills [76,77].

The case study of car tire production and disposal highlights the complex interplay between industrial processes, product use, and end-of-life scenarios. This complexity emphasizes the need for strategic measures to minimize microplastic release and its adverse effects on the environment. Integrating microplastic assessment into the LCA framework provides a comprehensive understanding of the real environmental consequences of plastic pollution, ensuring a more informed approach to sustainable plastic management and facilitating strategic decision-making throughout the entire life cycle.

2.4. Policy and Regulation

The effective mitigation of microplastic pollution depends on the implementation of comprehensive policies and robust regulations governing the entire life cycle of plastics. This section emphasizes the importance of a regulatory framework to guide the production, use, and disposal of MPs. Establishing comprehensive guidelines for the plastic life cycle serves as a cornerstone in mitigating the persistent impact of microplastics on ecosystems and human health.

2.4.1. Comprehensive Policies as Pillars of Mitigation

Although political measures to combat microplastic pollution are becoming increasingly important, they remain relatively rare compared to issues such as plastic bag pollution. As of mid-2019, only nine national governments, primarily in Europe and North America, had implemented policies. These policies often focus on banning plastic microbeads in cosmetic products or implementing planning requirements, with limited consideration for other sources such as synthetic tire abrasion. Unfortunately, the research landscape lacks comprehensive studies examining the effectiveness of policy instruments specifically targeted at addressing microplastic pollution [78].

In a noteworthy development in microplastic regulation, the European Union (EU) took a crucial step in September 2023 by introducing Commission Regulation (EU) 2023/2055. This regulation aims to restrict the use of synthetic microparticles, whether used individually or intentionally mixed into various products. It is worth highlighting that loose plastic glitter falls within the scope of this restriction. The legislation also includes transitional periods for specific applications, such as glitter in cosmetics and detergents [79].

Effective policies are instrumental in addressing the escalating challenge of microplastic pollution by imposing restrictions on irresponsible plastic production and encouraging the adoption of eco-friendly practices within the industry. However, the current emphasis on policies often neglects important aspects, including patterns of overconsumption and the entire life cycle of plastics. Countries like those in the European Union have set exemplary standards by implementing bans on single-use plastics and promoting plastic waste reduction initiatives [80]. To enhance the overall value of protective measures against MPs, policy interventions should extend beyond production limitations. These actions involve obtaining essential data for prevention planning, closing the microplastic loop from landfills and WWTPs, implementing quality control measures for plastic recovery and upcycling, and ensuring the proper disposal of abandoned plastic items [81].

In a recent ruling [82], a global manufacturer of resins and petrochemicals was found in violation of its discharge permit under the US Clean Water Act (CWA). The court ruled that the company was discharging plastic pellets and PVC powder into a surface water body, directly violating the permit term, which clearly prohibited the “discharge of floating solids or visible foam in other than trace amounts". This case highlights the crucial role of a robust legal framework in regulating and limiting environmentally harmful practices.

The entire life cycle of plastics is fundamentally political, although it has not been equally politicized across its stages. Therefore, responses and initiatives in policymaking should avoid seeking solutions solely in technological fixes or individual behavior adjustments. Instead, they must directly address the systemic, large-scale economic and political structures, as well as prevailing norms and practices, that uphold unsustainable patterns of production and consumption [83]. The implementation of strict standards and penalties for non-compliance through policies serves to encourage stakeholders to adopt environmentally conscious practices. This approach effectively mitigates the introduction of MPs into the environment.

2.4.2. The Need for International Cooperation

Microplastic pollution is a global challenge that goes beyond national boundaries. A comprehensive solution requires international cooperation and collaboration among nations. Pivotal milestones in addressing microplastic pollution on an international scale include the United Nations Environment Assembly (UNEA) in 2014 and the Basel Convention in 2017. Organizations such as the United Nations, along with initiatives like the UN Environment Programme (UNEP), provide platforms for global cooperation and collaborative efforts in combating microplastic pollution and publicizing crucial information [11,84].

Collective efforts can play a critical role in establishing shared standards and policies for plastic production, usage, and disposal. In addition to the imperative for collaborative efforts in formulating shared standards and policies for plastic management, there is a pressing need for international policy frameworks to address challenges arising from marine accidents. Cases such as falling containers, particularly those associated with MPs, and plastic releases resulting from natural disasters like storms or leakage, demand strategic involvements on a global scale [85,86].

Collaborative research and data sharing can enhance our understanding of microplastic pollution and facilitate the development of uniform methodologies for monitoring and assessment. International agreements further initiative-coordinated action, encouraging the exchange of information, and mobilizing resources to effectively address the widespread issue of microplastic pollution.

2.5. Education and Awareness

Raising public awareness and promoting educational initiatives are crucial components in the ongoing battle against microplastic pollution. This section emphasizes the significance of educating the public about MPs and their adverse effects on the environment and human health. The significance of public education is underscored, recognizing that an informed and engaged community plays a pivotal role in implementing effective measures to reduce microplastic pollution.

2.5.1. Public Awareness Campaigns

The subject of microplastic pollution remains relatively novel, even for experts in the field, indicating a significant knowledge gap that extends to the broader public. In two separate cases examining public awareness about MPs, a noteworthy trend occurred. The findings revealed that a considerable majority, exceeding 50% of the participants who were students, had limited knowledge about MPs. Specifically, 41% of the respondents fell into this category, and an even more significant majority, surpassing 63%, believed that the government is responsible for controlling MPs. This lack of awareness was more pronounced among educated populations, with social media identified as the primary source for self-education, a finding presented by [87]. In a similar survey, ref. [88] further pointed to the limited recognition of MPs among respondents, with only 26% reporting prior awareness of the issue.

Acknowledging this significant knowledge gap, it becomes evident that effective public awareness campaigns are instrumental in bridging the knowledge divide and educating communities about the far-reaching consequences of MPs. These campaigns should adopt diverse approaches, using clear and accessible information to explain the sources, risks, and consequences of MPs in the environment. Strategic tools such as infographics, videos, social media campaigns, and community events serve as powerful mediums for translating complex scientific information into digestible content for the public. By encouraging behavioral changes, such as reducing single-use plastics and practising responsible waste disposal, these campaigns empower individuals to take practical actions against microplastic pollution [89].

2.5.2. Integration into Educational Courses

Integrating the topic of MPs into educational courses, from primary schools to universities, stands as a required measure for promoting a deeper understanding of this emerging environmental challenge. By including this subject in science, geography, and environmental studies courses, students can gain early insights into the issue. Engaging in practical experiments and classroom discussions not only illuminates the profound impact of MPs on the ecosystem, but also raises a sense of responsibility and environmental stewardship among the younger generation. Educational institutions thus play a crucial role in shaping environmentally conscious citizens who are equipped to address the challenges posed by microplastic pollution [90–93].

2.5.3. Public Engagement and Citizen Science

Engaging the public in scientific activities through citizen science projects can significantly contribute to the monitoring and understanding of microplastic pollution. Involving citizens in data collection, whether through activities like beach cleanups, sample collection, or data analysis, raises a sense of ownership and active participation. Additionally, citizen science projects promote a deeper connection between communities and their local environments, motivating sustained efforts to combat microplastic pollution [94,95]. Educational initiatives and public engagement programs work in harmony to initiate a society that is not only well-informed but also actively committed to mitigating the impacts of microplastic pollution. The distribution of knowledge and active involvement become crucial instruments in this collective effort.

2.6. Industry Collaboration and Innovation

Industry collaboration and innovation are essential components in combating microplastic pollution. The interconnection of industries in mitigating this global challenge is highlighted, emphasizing the necessity for a joint approach. Furthermore, this section explores the role of innovation as a driving force, particularly in the redesign of materials and processes that align with sustainability goals. This collaboration and innovation nexus becomes a transformative force in reducing the footprint of MPs.

2.6.1. Collaborative Initiatives

Inter-industry collaboration is vital in addressing the microplastic issue at its source, particularly in areas that have been inadequately addressed, such as the release of MPs from WWTPs. Research indicates that conventional WWTPs can effectively separate around 90% of MPs influent [96]. However, a global study by [97] across 38 WWTPs in 11 countries found that over 50% of influent MPs are still discharged into the environment. Despite variations in reported statistics, there is a clear understanding that the release of MPs from WWTPs is alarmingly high, requiring urgent action [98].

Various methods for the separation of MPs, especially from water and wastewater, have been proposed by the scientific community in recent years, as detailed in the review by [99]. One innovative separation method, introduced by [100], employs the clean and cost-effective energy of a magnetic force. This novel technology offers a promising solution for efficiently separating MPs from wastewater outflows. Collaborations among industries are essential for developing comprehensive strategies that can significantly mitigate the release of microplastics into the environment. These collective efforts have the potential to drive the adoption of sustainable practices and contribute to substantial reductions in microplastic pollution across different sectors.

2.6.2. Innovation in Material Development and Production

Advancements in material science and production processes play a critical role in mitigating the risk of microplastic pollution. It is an obligation for research and development efforts to be directed towards crafting materials that possess characteristics such as biodegradability, compostability, or easy recyclability, thus minimizing the risk of transforming into harmful MPs. The case of some bioplastics, despite being publicized as environmentally friendly, raises concerns as they may not be truly biodegradable or compostable, leading to MPs pollution issues similar to petroleum-based plastics. Even though derived from biological sources, their decomposition can result in the generation of micro and nano plastics, declaring separate processing and composting. This challenges their presumed eco-friendliness and poses more severe threats to human health than conventional non-biodegradable MPs [101,102].

Furthermore, innovations in waste reduction technologies, demonstrated by additive manufacturing using recycled materials in 3D printing, offer promising avenues for repurposing waste and diminishing plastic pollution [103]. These technological advances have the potential to revolutionize industries by aligning production practices with environmental sustainability objectives. However, it is essential to recognize that technological solutions should work together, and not replace protective methods such as the adoption of sustainable materials and improved waste management. The ultimate goal is to reduce dependence on cleanup technologies, as emphasized by experts in the field [78,104].

2.6.3. Eco-Friendly Packaging and Single-Use Product Design

Approximately two-thirds of plastic waste originates from plastics with lifetimes of under five years, and packaging alone contributes 40% to this concerning statistic [58]. In 2021, single-use plastic waste, as reported by [105], reached 139 Mt, equivalent to the greenhouse gas emissions of the entire United Kingdom, amounting to approximately 460 Mt of CO_2e. In the study conducted by [106], single-use plastics including bags, wrappers, and food containers, constitute a significant portion of litter, ranging from 50% to 88% across various environments.

To prevent microplastic pollution, an essential strategy involves innovations in packaging and product design. Manufacturers should prioritize the development of packaging that minimizes both waste and the release of MPs during usage and disposal. This initiative includes designing packaging that is easily recyclable, incorporating sustainable materials, or exploring package-free alternatives. Moreover, industries should adopt circular economy principles in product design, promoting reuse and recycling to diminish the overall production of plastic waste [65]. Applying eco-conscious product design and packaging practices can play a critical role in reducing MPs.

2.7. Ecological Restoration

This section highlights the importance of ecological restoration in mitigating the impacts of microplastic pollution on ecosystems and biodiversity. It shows the necessity of integrating this element into a comprehensive approach to effectively rehabilitate the aftermath of microplastic pollution in ecosystems.

2.7.1. Strategic Repair of Ecosystems

Microplastic pollution imposes complex damage on living and non-living ecosystems, as explained throughout the various sections of this article. In living ecosystems, the risk posed by MPs to wildlife is evident, resulting in consequences such as physical harm, malnutrition, and fatal outcomes upon ingestion by marine animals, birds, and terrestrial organisms [107–109]. The presence of MPs disrupts natural ecosystem processes, altering the behavior and feeding patterns of organisms, thus triggering cascading effects throughout the ecosystem (refer to Section 2.1.1). Conversely, in non-living ecosystems, MPs cast a pervasive impact and contaminate soils, affecting structure and nutrient cycling, influencing plant growth, and impacting microbial communities [110–112]. Water bodies, integral components of these ecosystems, become compromised as MPs adsorb pollutants and release harmful chemicals, threatening aquatic ecosystems. Furthermore, the atmospheric transport of MPs raises concerns about air quality and the potential introduction of these particles to new ecosystems.

The escalating extent of human-induced damage to Earth's ecosystems necessitates a comprehensive strategy for ecosystem repair, positioning restoration ecology as a crucial component for our future survival. This concept holds significant relevance when applied to microplastic pollution, where ecosystems are adversely impacted [113]. Adopting restoration ecology principles becomes essential for mitigating the damage caused by MPs. Recognizing the dynamic nature of ecosystems affected by MPs, restoration goals should focus on future desired characteristics rather than static attributes from the past [114]. The concepts of restoration, reintroduction, and rewilding discussed in the context of land abandonment can also be applied to areas damaged by microplastic pollution and the wildlife affected by it. The reintroduction of native species that may have been impacted or displaced by MPs is analogous to efforts to return species to their former habitats. Additionally, rewilding, which involves allowing managed areas to return to a more natural and wild state, can be applied to regions affected by MPs, promoting the recovery of wildlife and ecosystems in the face of pollution [115].

Clear and achievable goals, informed by a thorough understanding of restoration options and their costs, are imperative in addressing the challenges posed by microplastic pollution. Additionally, developing effective and measurable success criteria, directly linked to restoration goals, is crucial in evaluating the success of restoration initiatives addressing the consequences of microplastic pollution [114].

2.7.2. A Holistic Approach to Restoration

While ecological restoration is of utmost importance, it needs to be part of a broader, holistic strategy to combat microplastic pollution effectively. A comprehensive approach should contain methods like reducing plastic usage, effective waste management, and policy implementation. Involving local communities, businesses, government agencies, and other stakeholders in decision-making processes can enhance the effectiveness and sustainability of restoration efforts. Community participation fosters a sense of ownership and responsibility for environmental stewardship, leading to more successful outcomes in restoring ecosystems affected by microplastic pollution. Furthermore, highlighting examples of successful community-led restoration projects and partnerships can inspire and guide similar initiatives in other regions or contexts [116,117]. Integrating restoration into this larger framework ensures that the restoration process aligns with the principle of sustainability and mitigates the risk of future microplastic pollution. Designing a holistic approach is essential to encourage the restoration of ecosystems in a manner that prevents recontamination and promotes sustainable and persistent recovery.

3. Conclusions

This article highlights our significant contribution in drawing up a comprehensive framework for understanding and addressing the issue of microplastic pollution. Through careful analysis, we projected global trends in plastic and microplastic production up to

2060 and generated original data, using newly published research as well as advanced data analysis methods. Our synthesized framework for microplastic mitigation encompasses various elements, including research and monitoring, waste management and recycling, circular economy principles, policy and regulation, education and awareness, industry collaboration and innovation, and ecological restoration. Drawing from existing research and our original insights, we have provided a broad understanding of how these components synergize to address the complex challenge of microplastic pollution. Our holistic approach, supported by previous research, underscores the urgency and complexity of the issue at hand.

Moving forward, collaborative efforts guided by the synthesized framework presented here and insights will be crucial in achieving tangible results in mitigating microplastic pollution and safeguarding our environment and health. Effectively combating this challenge requires a unified effort from individuals, industries, governments, and the global community. A comprehensive action plan, as outlined in this manuscript, is essential for systematically navigating this environmental challenge and raising awareness to combat microplastic pollution.

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References

1. Emberson-Marl, H.; Coppock, R.L.; Cole, M.J.; Godley, B.J.; Mimpriss, N.; Nelms, S.E.; Lindeque, P.K. MPs in the Arctic: A transect through the Barents Sea. *Front. Mar. Sci.* **2023**, *10*, 1241829. [CrossRef]
2. Pasolini, F.; Walther, B.A.; Bergmann, M. Citizen scientists reveal small but concentrated amounts of fragmented microplastic on Arctic beaches. *Front. Environ. Sci.* **2023**, *11*, 1210019. [CrossRef]
3. Kukkola, A.; Runkel, R.L.; Schneidewind, U.; Murphy, S.F.; Kelleher, L.; Smith, G.H.S.; Nel, H.A.; Lynch, I.; Krause, S. Prevailing impacts of river management on microplastic transport in contrasting US streams: Rethinking global microplastic flux estimations. *Water Res.* **2023**, *240*, 120112. [CrossRef] [PubMed]
4. Strokal, M.; Vriend, P.; Bak, M.P.; Kroeze, C.; van Wijnen, J.; van Emmerik, T. River export of macro- and microplastics to seas by sources worldwide. *Nat. Commun.* **2023**, *14*, 4842. [CrossRef] [PubMed]
5. Quilliam, R.S.; Pow, C.J.; Shilla, D.J.; Mwesiga, J.J.; Shilla, D.A.; Woodford, L. Microplastics in agriculture—A potential novel mechanism for the delivery of human pathogens onto crops. *Front. Plant Sci.* **2023**, *14*, 1152419. [CrossRef] [PubMed]
6. Jahandari, A. Microplastics in the urban atmosphere: Sources, occurrences, distribution, and potential health implications. *J. Hazard. Mater. Adv.* **2023**, *12*, 100346. [CrossRef]
7. Guo, J.J.; Huang, X.P.; Xiang, L.; Wang, Y.Z.; Li, Y.W.; Li, H.; Cai, Q.Y.; Mo, C.H.; Wong, M.H. Source, migration and toxicology of microplastics in soil. *Environ. Int.* **2020**, *137*, 105263. [CrossRef]
8. Eriksen, M.; Cowger, W.; Erdle, L.M.; Coffin, S.; Villarrubia-Gómez, P.; Moore, C.J.; Carpenter, E.J.; Day, R.H.; Thiel, M.; Wilcox, C. A growing plastic smog, now estimated to be over 170 trillion plastic particles afloat in the world's oceans—Urgent solutions required. *PLoS ONE* **2023**, *18*, e0281596. [CrossRef]
9. Allen, S.; Allen, D.; Moss, K.; Le Roux, G.; Phoenix, V.R.; Sonke, J.E. Examination of the ocean as a source for atmospheric microplastics. *PLoS ONE* **2020**, *15*, e0232746. [CrossRef]

10. Siddiqui, S.A.; Singh, S.; Bahmid, N.A.; Shyu, D.J.; Domínguez, R.; Lorenzo, J.M.; Pereira, J.A.; Câmara, J.S. Polystyrene microplastic particles in the food chain: Characteristics and toxicity. *Sci. Total Environ.* **2023**, *892*, 164531. [CrossRef]
11. Ghosh, S.; Sinha, J.K.; Ghosh, S.; Vashisth, K.; Han, S.; Bhaskar, R. MPs as an emerging threat to the global environment and human health. *Sustainability* **2023**, *15*, 10821. [CrossRef]
12. Saeedi, M. How microplastics interact with the food chain: A short overview of fate and impacts. *J. Food Sci. Technol.* **2024**, *61*, 403–413. [CrossRef]
13. Leslie, H.A.; Van Velzen, M.J.; Brandsma, S.H.; Vethaak, A.D.; Garcia-Vallejo, J.J.; Lamoree, M.H. Discovery and quantification of plastic particle pollution in human blood. *Environ. Int.* **2022**, *163*, 107199. [CrossRef] [PubMed]
14. Ragusa, A.; Svelato, A.; Santacroce, C.; Catalano, P.; Notarstefano, V.; Carnevali, O.; Papa, F.; Rongioletti, M.C.A.; Baiocco, F.; Draghi, S.; et al. Plasticenta: First evidence of microplastics in human placenta. *Environ. Int.* **2021**, *146*, 106274. [CrossRef] [PubMed]
15. Kopatz, V.; Wen, K.; Kovács, T.; Keimowitz, A.S.; Pichler, V.; Widder, J.; Vethaak, A.D.; Hollóczki, O.; Kenner, L. Micro- and Nanoplastics Breach the Blood–Brain Barrier (BBB): Biomolecular Corona's Role Revealed. *Nanomaterials* **2023**, *13*, 1404. [CrossRef] [PubMed]
16. Zhu, X.; Wang, C.; Duan, X.; Liang, B.; Xu, E.G.; Huang, Z. Micro-and nanoplastics: A new cardiovascular risk factor? *Environ. Int.* **2023**, *171*, 107662. [CrossRef] [PubMed]
17. Prüst, M.; Meijer, J.; Westerink, R.H. The plastic brain: Neurotoxicity of micro-and nanoplastics. *Part. Fibre Toxicol.* **2020**, *17*, 24. [CrossRef] [PubMed]
18. Kuroiwa, M.; Yamaguchi, S.I.; Kato, Y.; Hori, A.; Toyoura, S.; Nakahara, M.; Morimoto, N.; Nakayama, M. Tim4, a macrophage receptor for apoptotic cells, binds polystyrene microplastics via aromatic-aromatic interactions. *Sci. Total Environ.* **2023**, *875*, 162586. [CrossRef]
19. Segovia-Mendoza, M.; Nava-Castro, K.E.; Palacios-Arreola, M.I.; Garay-Canales, C.; Morales-Montor, J. How microplastic components influence the immune system and impact on children health: Focus on cancer. *Birth Defects Res.* **2020**, *112*, 1341–1361. [CrossRef]
20. Pellegrino, A.; Danne, D.; Weigel, C.; Seitz, H. An In Vitro Assay to Quantify Effects of Micro-and Nano-Plastics on Human Gene Transcription. *Microplastics* **2023**, *2*, 122–131. [CrossRef]
21. Nikpay, M. Wastewater fines influence the adsorption behavior of pollutants onto MPs. *J. Polym. Environ.* **2022**, *30*, 776–783. [CrossRef]
22. Tang, Y.; Liu, Y.; Chen, Y.; Zhang, W.; Zhao, J.; He, S.; Yang, C.; Zhang, T.; Tang, C.; Zhang, C.; et al. A review: Research progress on microplastic pollutants in aquatic environments. *Sci. Total Environ.* **2021**, *766*, 142572. [CrossRef] [PubMed]
23. Pivokonsky, M.; Cermakova, L.; Novotna, K.; Peer, P.; Cajthaml, T.; Janda, V. Occurrence of microplastics in raw and treated drinking water. *Sci. Total Environ.* **2018**, *643*, 1644–1651. [CrossRef] [PubMed]
24. Gambino, I.; Bagordo, F.; Grassi, T.; Panico, A.; De Donno, A. Occurrence of microplastics in tap and bottled water: Current knowledge. *Int. J. Environ. Res. Public Health* **2022**, *19*, 5283. [CrossRef] [PubMed]
25. Osorio, E.D.; Tanchuling, M.A.N.; Diola, M.B.L.D. Microplastics occurrence in surface waters and sediments in five river mouths of Manila Bay. *Front. Environ. Sci.* **2021**, *9*, 719274. [CrossRef]
26. Gerolin, C.R.; Pupim, F.N.; Sawakuchi, A.O.; Grohmann, C.H.; Labuto, G.; Semensatto, D. Microplastics in sediments from Amazon rivers, Brazil. *Sci. Total Environ.* **2020**, *749*, 141604. [CrossRef] [PubMed]
27. Amelia, T.S.M.; Khalik, W.M.A.W.M.; Ong, M.C.; Shao, Y.T.; Pan, H.J.; Bhubalan, K. Marine microplastics as vectors of major ocean pollutants and its hazards to the marine ecosystem and humans. *Prog. Earth Planet. Sci.* **2021**, *8*, 12. [CrossRef]
28. Lofty, J.; Muhawenimana, V.; Wilson, C.A.M.E.; Ouro, P. Microplastics removal from a primary settler tank in a wastewater treatment plant and estimations of contamination onto European agricultural land via sewage sludge recycling. *Environ. Pollut.* **2022**, *304*, 119198. [CrossRef]
29. Ryan, A.C.; Allen, D.; Allen, S.; Maselli, V.; LeBlanc, A.; Kelleher, L.; Krause, S.; Walker, T.R.; Cohen, M. Transport and deposition of ocean-sourced microplastic particles by a North Atlantic hurricane. *Commun. Earth Environ.* **2023**, *4*, 442. [CrossRef]
30. Romera-Castillo, C.; Lucas, A.; Mallenco-Fornies, R.; Briones-Rizo, M.; Calvo, E.; Pelejero, C. Abiotic plastic leaching contributes to ocean acidification. *Sci. Total Environ.* **2023**, *854*, 158683. [CrossRef]
31. Buwono, N.R.; Risjani, Y.; Soegianto, A. Distribution of microplastic in relation to water quality parameters in the Brantas River, East Java, Indonesia. *Environ. Technol. Innov.* **2021**, *24*, 101915. [CrossRef]
32. Kvale, K.; Prowe, A.E.F.; Chien, C.T.; Landolfi, A.; Oschlies, A. Zooplankton grazing of microplastic can accelerate global loss of ocean oxygen. *Nat. Commun.* **2021**, *12*, 2358. [CrossRef] [PubMed]
33. Malinowski, C.R.; Searle, C.L.; Schaber, J.; Höök, T.O. Microplastics impact simple aquatic food web dynamics through reduced zooplankton feeding and potentially releasing algae from consumer control. *Sci. Total Environ.* **2023**, *904*, 166691. [CrossRef] [PubMed]
34. Merrill, G.B.; Hermabessiere, L.; Rochman, C.M.; Nowacek, D.P. Microplastics in marine mammal blubber, melon, & other tissues: Evidence of translocation. *Environ. Pollut.* **2023**, *335*, 122252. [PubMed]

35. Mofijur, M.; Fattah, I.R.; Alam, M.A.; Islam, A.S.; Ong, H.C.; Rahman, S.A.; Najafi, G.; Ahmed, S.F.; Uddin, M.A.; Mahlia, T.M.I. Impact of COVID-19 on the social, economic, environmental and energy domains: Lessons learnt from a global pandemic. *Sustain. Prod. Consum.* **2021**, *26*, 343–359. [CrossRef]
36. PlasticsEurope. Plastics—The Facts 2023. Available online: https://plasticseurope.org/wp-content/uploads/2023/10/Plasticsthefastfacts2023-1.pdf (accessed on 1 December 2023).
37. Hupfer, C. The Plastic Industry Berlin Aug 2016—Copy.pdf. 'PowerPoint-Präsentation'. Available online: https://committee.iso.org/files/live/sites/tc61/files (accessed on 16 January 2024).
38. Ryberg, M.W.; Hauschild, M.Z.; Wang, F.; Averous-Monnery, S.; Laurent, A. Global environmental losses of plastics across their value chains. *Resour. Conserv. Recycl.* **2019**, *151*, 104459. [CrossRef]
39. Boucher, J.; Friot, D. *Primary Microplastics in the Oceans: A Global Evaluation of Sources*; IUCN: Gland, Switzerland, 2017.
40. Tatsii, D.; Bucci, S.; Bhowmick, T.; Guettler, J.; Bakels, L.; Bagheri, G.; Stohl, A. Shape matters: Long-range transport of microplastic fibers in the atmosphere. *Environ. Sci. Technol.* **2023**, *58*, 671–682. [CrossRef] [PubMed]
41. Lamichhane, G.; Acharya, A.; Marahatha, R.; Modi, B.; Paudel, R.; Adhikari, A.; Raut, B.K.; Aryal, S.; Parajuli, N. MPs in environment: Global concern, challenges, and controlling measures. *Int. J. Environ. Sci. Technol.* **2023**, *20*, 4673–4694. [CrossRef]
42. Preferred Fiber & Materials Market Report, October 2022. Textile Exchange. Available online: https://textileexchange.org/knowledge-center/reports/materials-market-report-2022/ (accessed on 15 February 2024).
43. Dreillard, M.; Barros, C.D.F.; Rouchon, V.; Emonnot, C.; Lefebvre, V.; Moreaud, M.; Guillaume, D.; Rimbault, F.; Pagerey, F. Quantification and morphological characterization of microfibers emitted from textile washing. *Sci. Total Environ.* **2022**, *832*, 154973. [CrossRef]
44. Jiang, J.; Wang, X.; Ren, H.; Cao, G.; Xie, G.; Xing, D.; Liu, B. Investigation and fate of microplastics in wastewater and sludge filter cake from a wastewater treatment plant in China. *Sci. Total Environ.* **2020**, *746*, 141378. [CrossRef]
45. Periyasamy, A.P.; Tehrani-Bagha, A. A review on microplastic emission from textile materials and its reduction techniques. *Polym. Degrad. Stab.* **2022**, *199*, 109901. [CrossRef]
46. Farrell, P.; Nelson, K. Trophic level transfer of microplastic: *Mytilus edulis* (L.) to *Carcinus maenas* (L.). *Environ. Pollut.* **2013**, *177*, 1–3. [CrossRef] [PubMed]
47. Pan, Y.; Long, Y.; Hui, J.; Xiao, W.; Yin, J.; Li, Y.; Liu, D.; Tian, Q.; Chen, L. MPs can affect the trophic cascade strength and stability of plankton ecosystems via behavior-mediated indirect interactions. *J. Hazard. Mater.* **2022**, *430*, 128415. [CrossRef] [PubMed]
48. Ma, M.; Wu, Z.; An, L.; Xu, Q.; Wang, H.; Zhang, Y.; Kang, Y. MPs transferring from abiotic to biotic in aquatic ecosystem: A mini review. *Sci. Total Environ.* **2023**, *893*, 164686. [CrossRef] [PubMed]
49. Passos, R.S.; Davenport, A.; Busquets, R.; Selden, C.; Silva, L.B.; Baptista, J.S.; Barceló, D.; Campos, L.C. MPs and nanoplastics in haemodialysis waters: Emerging threats to be in our radar. *Environ. Toxicol. Pharmacol.* **2023**, *893*, 164686.
50. Protyusha, G.B.; Kavitha, B.; Robin, R.S.; Nithin, A.; Ineyathendral, T.R.; Shivani, S.S.; Anandavelu, I.; Sivasamy, S.; Samuel, V.D.; Purvaja, R. MPs in oral healthcare products (OHPs) and their environmental health risks and mitigation measures. *Environ. Pollut.* **2023**, *343*, 123118. [CrossRef] [PubMed]
51. Miller, E.; Sedlak, M.; Lin, D.; Box, C.; Holleman, C.; Rochman, C.M.; Sutton, R. Recommended best practices for collecting, analyzing, and reporting MPs in environmental media: Lessons learned from comprehensive monitoring of San Francisco Bay. *J. Hazard. Mater.* **2021**, *409*, 124770. [CrossRef]
52. Chen, Y.N.; Rani, A.; Chiang, C.Y.; Kim, H.; Pan, S.Y. Monitoring, control and assessment of MPs in bioenvironmental systems. *Environ. Technol. Innov.* **2023**, *32*, 103250. [CrossRef]
53. Joyce, H.; Nash, R.; Frias, J.; White, J.; Cau, A.; Carreras-Colom, E.; Kavanagh, F. Monitoring microplastic pollution: The potential and limitations of Nephrops norvegicus. *Ecol. Indic.* **2023**, *154*, 110441. [CrossRef]
54. Claro, F.; Fossi, M.C.; Ioakeimidis, C.; Baini, M.; Lusher, A.L.; McFee, W.; McIntosh, R.R.; Pelamatti, T.; Sorce, M.; Galgani, F.; et al. Tools and constraints in monitoring interactions between marine litter and megafauna: Insights from case studies around the world. *Mar. Pollut. Bull.* **2019**, *141*, 147–160. [CrossRef]
55. Jeong, H.; Lee, Y.H.; Sayed, A.E.D.H.; Jeong, C.B.; Zhou, B.; Lee, J.S.; Byeon, E. Short- and long-term single and combined effects of MPs and chromium on the freshwater water flea Daphnia magna. *Aquat. Toxicol.* **2022**, *253*, 106348. [CrossRef] [PubMed]
56. Anderson-Grégoire, I.M.; Horner, K.A.; Leung, C.K.; Leboe-McGowan, D.S.; Olawoyin, A.M.; Reydman, B.; Cuzzocrea, A. A big data science solution for analytics on moving objects. In Proceedings of the International Conference on Advanced Information Networking and Applications, Toronto, ON, Canada, 12–14 May 2021; Springer International Publishing: Cham, Switzerland, 2021.
57. Zhang, Y.; Zhang, D.; Zhang, Z. A Critical Review on Artificial Intelligence—Based MPs Imaging Technology: Recent Advances, Hot-Spots and Challenges. *Int. J. Environ. Res. Public Health* **2023**, *20*, 1150. [CrossRef] [PubMed]
58. OECD. Plastic Waste Management Challenges. 2023. Available online: https://www.oecd.org/coronavirus/en/data-insights/plastic-waste-management-challenges (accessed on 5 January 2024).
59. Chamas, A.; Moon, H.; Zheng, J.; Qiu, Y.; Tabassum, T.; Jang, J.H.; Abu-Omar, M.; Scott, S.L.; Suh, S. Degradation rates of plastics in the environment. *ACS Sustain. Chem. Eng.* **2020**, *8*, 3494–3511. [CrossRef]
60. Napper, I.E.; Thompson, R.C. Environmental deterioration of biodegradable, oxo-biodegradable, compostable, and conventional plastic carrier bags in the sea, soil, and open-air over a 3-year period. *Environ. Sci. Technol.* **2019**, *53*, 4775–4783. [CrossRef] [PubMed]

61. Brown, E.; MacDonald, A.; Allen, S.; Allen, D. The potential for a plastic recycling facility to release microplastic pollution and possible filtration remediation effectiveness. *J. Hazard. Mater. Adv.* **2023**, *10*, 100309. [CrossRef]
62. Kallenbach, E.M.; Eriksen, T.E.; Hurley, R.R.; Jacobsen, D.; Singdahl-Larsen, C.; Friberg, N. Plastic recycling plant as a point source of MPs to sediment and macroinvertebrates in a remote stream. *MPs Nanoplastics* **2022**, *2*, 26. [CrossRef] [PubMed]
63. Willis, K.; Maureaud, C.; Wilcox, C.; Hardesty, B.D. How successful are waste abatement campaigns and government policies at reducing plastic waste into the marine environment? *Mar. Policy* **2018**, *96*, 243–249. [CrossRef]
64. Walker, T.R.; Fequet, L. Current trends of unsustainable plastic production and micro (nano) plastic pollution. *TrAC Trends Anal. Chem.* **2023**, *160*, 116984. [CrossRef]
65. Geyer, R.; Jambeck, J.R.; Law, K.L. Production, use, and fate of all plastics ever made. *Sci. Adv.* **2017**, *3*, e1700782. [CrossRef]
66. Prata, J.C.; Silva, A.L.P.; Da Costa, J.P.; Mouneyrac, C.; Walker, T.R.; Duarte, A.C.; Rocha-Santos, T. Solutions and integrated strategies for the control and mitigation of plastic and microplastic pollution. *Int. J. Environ. Res. Public Health* **2019**, *16*, 2411. [CrossRef]
67. Leong, S.Y.; Lee, S.Y.; Koh, T.Y.; Ang, D.T.C. 4R of rubber waste management: Current and outlook. *J. Mater. Cycles Waste Manag.* **2023**, *25*, 37–51. [CrossRef] [PubMed]
68. Pouikli, K. Concretising the role of extended producer responsibility in European Union waste law and policy through the lens of the circular economy. In *ERA Forum*; Springer: Berlin/Heidelberg, Germany, 2020; Volume 20, pp. 491–508.
69. Syberg, K.; Nielsen, M.B.; Oturai, N.B.; Clausen, L.P.W.; Ramos, T.M.; Hansen, S.F. Circular economy and reduction of micro (nano) plastics contamination. *J. Hazard. Mater. Adv.* **2022**, *5*, 100044. [CrossRef]
70. Zhao, X.; You, F. Life cycle assessment of MPs reveals their greater environmental hazards than mismanaged polymer waste losses. *Environ. Sci. Technol.* **2022**, *56*, 11780–11797. [CrossRef] [PubMed]
71. Salieri, B.; Stoudmann, N.; Hischier, R.; Som, C.; Nowack, B. How relevant are direct emissions of MPs into freshwater from an LCA perspective? *Sustainability* **2021**, *13*, 9922. [CrossRef]
72. Corella-Puertas, E.; Hajjar, C.; Lavoie, J.; Boulay, A.M. MarILCA characterization factors for microplastic impacts in life cycle assessment: Physical effects on biota from emissions to aquatic environments. *J. Clean. Prod.* **2023**, *418*, 138197. [CrossRef]
73. Saling, P.; Gyuzeleva, L.; Wittstock, K.; Wessolowski, V.; Griesshammer, R. Life cycle impact assessment of MPs as one component of marine plastic debris. *Int. J. Life Cycle Assess.* **2020**, *25*, 2008–2026. [CrossRef]
74. Baensch-Baltruschat, B.; Kocher, B.; Stock, F.; Reifferscheid, G. Tyre and road wear particles (TRWP)—A review of generation, properties, emissions, human health risk, ecotoxicity, and fate in the environment. *Sci. Total Environ.* **2020**, *733*, 137823. [CrossRef]
75. Kole, P.J.; Löhr, A.J.; Van Belleghem, F.G.; Ragas, A.M. Wear and tear of tyres: A stealthy source of MPs in the environment. *Int. J. Environ. Res. Public Health* **2017**, *14*, 1265. [CrossRef]
76. Wan, Y.; Chen, X.; Liu, Q.; Hu, H.; Wu, C.; Xue, Q. Informal landfill contributes to the pollution of microplastics in the surrounding environment. *Environ. Pollut.* **2022**, *293*, 118586. [CrossRef]
77. Nayahi, N.T.; Ou, B.; Liu, Y.; Janjaroen, D. Municipal solid waste sanitary and open landfills: Contrasting sources of microplastics and its fate in their respective treatment systems. *J. Clean. Prod.* **2022**, *380*, 135095. [CrossRef]
78. Karasik, R.; Vegh, T.; Diana, Z.; Bering, J.; Caldas, J.; Pickle, A.; Rittschof, D.; Virdin, J. Years of government responses to the global plastic pollution problem: The plastics policy inventory. In *NI X 20-05*; Duke University: Durham, NC, USA, 2020; Volume 20, pp. 20–105.
79. European Commission. Commission Regulation (EU) 2023/2055 on the Restriction of MPs Intentionally Added to Products. Available online: https://single-market-economy.ec.europa.eu/commission-regulation-eu-20232055-restriction-MPs-intentionally-added-products_en (accessed on 9 January 2024).
80. European Commission. Commission Guidelines on Single-Use Plastic Products. Perma.cc. Available online: https://perma.cc/RE7L-XSV9 (accessed on 9 January 2024).
81. Hettiarachchi, H.; Meegoda, J.N. Microplastic Pollution Prevention: The Need for Robust Policy Interventions to Close the Loopholes in Current Waste Management Practices. *Int. J. Environ. Res. Public Health* **2023**, *20*, 6434. [CrossRef] [PubMed]
82. San Antonio Bay Estuarine Waterkeeper v. Formosa Plastics Corp. Tex. (No. 20-40575). United States Court of Appeals for the Fifth Circuit. 30 April 2021. Available online: https://casetext.com/case/san-antonio-bay-estuarine-waterkeeper-v-formosa-plastics-corp-tex (accessed on 11 January 2024).
83. Nielsen, T.D.; Hasselbalch, J.; Holmberg, K.; Stripple, J. Politics and the plastic crisis: A review throughout the plastic life cycle. *Wiley Interdiscip. Rev. Energy Environ.* **2020**, *9*, e360. [CrossRef]
84. McGlade, J.; Samy Fahim, I.; Green, D.; Landrigan, P.; Andrady, A.; Costa, M.; Geyer, R.; Gomes, R.; Tan Shau Hwai, A.; Jambeck, J.; et al. From pollution to solution: A global assessment of marine litter and plastic pollution. *Mar. Pollut. Bull.* **2021**, *141*. Available online: https://research.usc.edu.au/esploro/outputs/report/From-Pollution-to-Solution-A-Global/99584903702621 (accessed on 15 January 2024).
85. Wan, S.; Yang, X.; Chen, X.; Qu, Z.; An, C.; Zhang, B.; Lee, K.; Bi, H. Emerging marine pollution from container ship accidents: Risk characteristics, response strategies, and regulation advancements. *J. Clean. Prod.* **2022**, *376*, 134266. [CrossRef]
86. Zhang, C.; Wang, Q.; Zhao, J.; Zhao, Y.; Shan, E. Observational and model studies on transport and inventory of microplastics from a leak accident on the beaches of Yantai. *Mar. Pollut. Bull.* **2022**, *182*, 113976. [CrossRef] [PubMed]
87. Omoyajowo, K.; Raimi, M.; Waleola, T.; Odipe, O.; Ogunyebi, A. Public awareness, knowledge, attitude and perception on MPs pollution around Lagos Lagoon. *Ecol. Saf. Balanc. Use Resour.* **2021**, *2*, 35–46.

88. Deng, L.; Cai, L.; Sun, F.; Li, G.; Che, Y. Public attitudes towards MPs: Perceptions, behaviors and policy implications. *Resour. Conserv. Recycl.* **2020**, *163*, 105096. [CrossRef]
89. Felipe-Rodriguez, M.; Böhm, G.; Doran, R. What does the public think about MPs? Insights from an empirical analysis of mental models elicited through free associations. *Front. Psychol.* **2022**, *13*, 920454. [CrossRef]
90. Krasny, M.E. *Advancing Environmental Education Practice*; Cornell University Press: Ithaca, NY, USA, 2020.
91. Raab, P.; Bogner, F.X. MPs in the environment: Raising awareness in primary education. *Am. Biol. Teach.* **2020**, *82*, 478–487. [CrossRef]
92. Araújo, J.L.; Morais, C.; Paiva, J.C. Students' attitudes towards the environment and marine litter in the context of a coastal water quality educational citizen science project. *Aust. J. Environ. Educ.* **2023**, *39*, 522–535. [CrossRef]
93. Lindemann-Matthies, P.; Hoyer, E.; Remmele, M. Collective Public Commitment: Young People on the Path to a More Sustainable Lifestyle. *Sustainability* **2021**, *13*, 11349. [CrossRef]
94. Nelms, S.E.; Easman, E.; Anderson, N.; Berg, M.; Coates, S.; Crosby, A.; Eisfeld-Pierantonio, S.; Eyles, L.; Flux, T.; Gilford, E.; et al. The role of citizen science in addressing plastic pollution: Challenges and opportunities. *Environ. Sci. Policy* **2022**, *128*, 14–23. [CrossRef]
95. Forrest, S.A.; Holman, L.; Murphy, M.; Vermaire, J.C. Citizen science sampling programs as a technique for monitoring microplastic pollution: Results, lessons learned and recommendations for working with volunteers for monitoring plastic pollution in freshwater ecosystems. *Environ. Monit. Assess.* **2019**, *191*, 172. [CrossRef] [PubMed]
96. Alvim, C.B.; Mendoza-Roca, J.A.; Bes-Piá, A. Wastewater treatment plant as MPs release source–Quantification and identification techniques. *J. Environ. Manag.* **2020**, *255*, 109739. [CrossRef] [PubMed]
97. Liu, W.; Zhang, J.; Liu, H.; Guo, X.; Zhang, X.; Yao, X.; Cao, Z.; Zhang, T. A review of the removal of MPs in global wastewater treatment plants: Characteristics and mechanisms. *Environ. Int.* **2021**, *146*, 106277. [CrossRef] [PubMed]
98. Woodward, J.; Li, J.; Rothwell, J.; Hurley, R. Acute riverine microplastic contamination due to avoidable releases of untreated wastewater. *Nat. Sustain.* **2021**, *4*, 793–802. [CrossRef]
99. Gao, W.; Zhang, Y.; Mo, A.; Jiang, J.; Liang, Y.; Cao, X.; He, D. Removal of microplastics in water: Technology progress and green strategies. *Green Anal. Chem.* **2022**, *3*, 100042. [CrossRef]
100. Nikpay, M. Method and Device for Separating Plastic Particles with a Magnetic Filter. Patent no. DE102022001154A1, 5 October 2023.
101. Shruti, V.C.; Kutralam-Muniasamy, G. Bioplastics: Missing link in the era of MPs. *Sci. Total Environ.* **2019**, *697*, 134139. [CrossRef]
102. Jiang, T.; Wu, X.; Yuan, S.; Lai, C.; Bian, S.; Yu, W.; Liang, S.; Hu, J.; Huang, L.; Duan, H.; et al. A potential threat from biodegradable MPs: Mechanism of cadmium adsorption and desorption in the simulated gastrointestinal environment. *Front. Environ. Sci. Eng.* **2024**, *18*, 19. [CrossRef]
103. Sanchez, F.A.C.; Boudaoud, H.; Camargo, M.; Pearce, J.M. Plastic recycling in additive manufacturing: A systematic literature review and opportunities for the circular economy. *J. Clean. Prod.* **2020**, *264*, 121602. [CrossRef]
104. Cordier, M.; Uehara, T. How much innovation is needed to protect the ocean from plastic contamination? *Sci. Total Environ.* **2019**, *670*, 789–799. [CrossRef] [PubMed]
105. Charles, D.; Kimman, L. *Plastic Waste Makers Index 2023*; Minderoo Foundation: Perth, Australia, 2023.
106. Morales-Caselles, C.; Viejo, J.; Martí, E.; González-Fernández, D.; Pragnell-Raasch, H.; González-Gordillo, J.I.; Montero, E.; Arroyo, G.M.; Hanke, G.; Salvo, V.S.; et al. An inshore–offshore sorting system revealed from global classification of ocean litter. *Nat. Sustain.* **2021**, *4*, 484–493. [CrossRef]
107. Bhuyan, M.S. Effects of microplastics on fish and in human health. *Front. Environ. Sci.* **2022**, *10*, 250. [CrossRef]
108. Mubin, A.N.; Arefin, S.; Mia, M.S.; Islam, A.R.M.T.; Bari, A.M.; Islam, M.S.; Ali, M.M.; Siddique, M.A.B.; Rahman, M.S.; Senapathi, V.; et al. Managing the invisible threat of microplastics in marine ecosystems: Lessons from the coast of the Bay of Bengal. *Sci. Total Environ.* **2023**, *889*, 164224. [CrossRef] [PubMed]
109. Wang, L.; Nabi, G.; Yin, L.; Wang, Y.; Li, S.; Hao, Z.; Li, D. Birds and plastic pollution: Recent advances. *Avian Res.* **2021**, *12*, 59. [CrossRef] [PubMed]
110. Kumar, A.; Mishra, S.; Pandey, R.; Yu, Z.G.; Kumar, M.; Khoo, K.S.; Thakur, T.K.; Show, P.L. Microplastics in terrestrial ecosystems: Un-ignorable impacts on soil characteristics, nutrient storage and its cycling. *TrAC Trends Anal. Chem.* **2023**, *158*, 116869. [CrossRef]
111. Rillig, M.C.; Leifheit, E.; Lehmann, J. Microplastic effects on carbon cycling processes in soils. *PLoS Biol.* **2021**, *19*, e3001130. [CrossRef]
112. He, D.; Luo, Y.; Lu, S.; Liu, M.; Song, Y.; Lei, L. MPs in soils: Analytical methods, pollution characteristics and ecological risks. *TrAC Trends Anal. Chem.* **2018**, *109*, 163–172. [CrossRef]
113. Gwenzi, W.; Simbanegavi, T.T.; Mahdi, H.I.; Azelee, N.I.W.; Muisa-Zikali, N.; Rangabhashiyam, S. Occurrence and ecological health risks of MPs. In *Emerging Contaminants in the Terrestrial-Aquatic-Atmosphere Continuum*; Elsevier: Amsterdam, The Netherlands, 2022.
114. Hobbs, R.J.; Harris, J.A. Restoration ecology: Repairing the earth's ecosystems in the new millennium. *Restor. Ecol.* **2001**, *9*, 239–246. [CrossRef]
115. Corlett, R.T. Restoration, reintroduction, and rewilding in a changing world. *Trends Ecol. Evol.* **2016**, *31*, 453–462. [CrossRef]

116. Onyena, A.P.; Aniche, D.C.; Ogbolu, B.O.; Rakib, M.R.J.; Uddin, J.; Walker, T.R. Governance strategies for mitigating microplastic pollution in the marine environment: A review. *Microplastics* **2021**, *1*, 15–46. [CrossRef]
117. Reichelt-Brushett, A. Pollution Mitigation and Ecological Restoration. In *Marine Pollution–Monitoring, Management and Mitigation*; Springer Nature: Cham, Switzerland, 2023.