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Review Article

Sectoral Sources, Industrial Use and Environmental Management of Microplastics: A Holistic Assessment

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Abstract: The aim of this study is to investigate the dual role of microplastics (MPs) as both widespread environmental contaminants and deliberately used functional materials across industrial sectors. It provides an integrated assessment of the sources, pathways, and applications of MPs, with a focus on their sector-specific dynamics. Microplastics, defined as synthetic polymer particles smaller than 5 mm, are emitted unintentionally through processes in industries such as cosmetics, textiles, food packaging, agriculture, and construction, often entering aquatic, terrestrial, and atmospheric ecosystems. Simultaneously, they are intentionally employed in various industrial applications including textiles, building materials, membrane and filtration technologies, medical systems, and energy production. This study critically evaluates both aspects by reviewing current literature and sectoral practices, emphasizing the advantages MPs provide—such as durability, lightweight structure, and chemical resistance—while also highlighting their persistent environmental footprint and risks to human health. These risks are amplified by their role as vectors for toxic pollutants, their bio-accumulative nature, and their long degradation times. The paper concludes that managing microplastic pollution demands a life cycle-oriented approach that spans from production to end-of-life, supported by innovation in biodegradable alternatives, stronger regulatory frameworks, and interdisciplinary environmental health research. Ultimately, the study contributes to the understanding of how industrial innovation can be aligned with sustainability and global environmental responsibility.

Keywords: *Microplastic, Microplastic Pollution, Microplastic Removal, Sectoral Pollution, Environmental Management.*

Mikroplastiklerin Sektörel Kaynakları, Endüstriyel Kullanımı ve Çevresel Yönetimi: Bütüncül Bir Değerlendirme

Öz: Bu çalışmanın amacı, mikroplastiklerin (MP'ler) hem yaygın çevre kirleticileri hem de endüstriyel sektörlerde kasıtlı olarak kullanılan işlevsel malzemeler olarak ikili rolünü araştırmaktır. MP'lerin kaynakları ve uygulamalarına ilişkin sektöre özgü dinamiklere odaklanarak bütünleşik bir değerlendirme sunmaktadır. 5 mm'den küçük sentetik polimer parçacıkları olarak tanımlanan MP'ler, kozmetik, tekstil, gıda ambalajı, tarım ve inşaat gibi endüstrilerdeki süreçler yoluyla kasıtsız olarak yayılır ve sıklıkla sucul, karasal ve atmosferik ekosistemlere girer. Aynı zamanda, tekstiller, yapı malzemeleri, membran ve filtrasyon teknolojileri, tıbbi sistemler ve enerji üretimi dahil olmak üzere çeşitli endüstriyel uygulamalarda kasıtlı olarak kullanılırlar. Bu çalışma, mevcut literatürü ve sektörel uygulamaları gözden geçirerek her iki yönü de eleştirel bir şekilde değerlendirir, MP'lerin sağladığı avantajları (dayanıklılık, hafif yapı ve kimyasal direnç gibi) vurgularken, aynı zamanda kalıcı çevresel ayak izlerini ve insan sağlığına yönelik riskleri de vurgulamaktadır. Bu riskler, toksik kirleticiler için vektörler olarak oynadıkları rol, biyolojik olarak birikebilen yapıları ve uzun bozunma süreleri nedeniyle daha da artar. Bu çalışma, MP kirliliğini yönetmenin, biyolojik olarak parçalanabilir alternatiflerdeki yenilikler, daha güçlü

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düzenleyici çerçeveler ve disiplinler arası çevre sağlığı araştırmalarıyla desteklenen, üretimden kullanım ömrünün sonuna kadar uzanan yaşam döngüsü odaklı bir yaklaşım gerektirdiği sonucuna varmaktadır. Sonuç olarak, çalışma endüstriyel yeniliğin sürdürülebilirlik ve küresel çevre sorumluluğuyla nasıl uyumlu hale getirilebileceğinin anlaşılmasına katkıda bulunmaktadır.

Anahtar Kelimeler: *Mikroplastik, Mikroplastik kirliliği, Mikroplastik Giderimi, Sektörel Kirlilik, Çevresel Yönetim.*

1. Introduction

Microplastics (MPs) are synthetic polymer particles generally smaller than 5 mm in diameter, and they enter the environment through both primary sources (direct production: cosmetics, cleaning products, etc.) and secondary sources (fragmentation of larger plastics via physical, chemical, or biological processes) [1]. Their large surface areas and hydrophobic structures increase their capacity to adsorb environmental toxic substances (e.g., heavy metals, pesticides, antibiotic residues), which poses a direct threat to both ecosystems and human health through bioaccumulation and biomagnification across the food chain [2,3]. The environmental impacts of microplastics are not limited to marine and freshwater ecosystems; they also disrupt soil microbiota [1], reduce agricultural productivity [4], spread through the atmosphere to reach humans via the respiratory tract [5], and have even been detected in drinking water [6]. The effects of MPs on living organisms include accumulation in the digestive system, reduced energy intake, stunted growth, inflammation, genotoxicity, endocrine disruption, and potential carcinogenicity [3,7]. Particularly in aquatic organisms, the density and accumulation of MPs vary according to biological factors such as habitat, feeding level, and trophic position, reaching up to 15.8 particles per organism in benthopelagic fish species [6]. MPs also negatively affect the carbon cycle and the carbon sequestration potential in aquatic environments [4]. In addition to conventional methods (coagulation, filtration, adsorption) used to control existing pollution, there has been an increasing trend toward advanced technologies in recent years. Especially, innovative materials such as magnetic nanoparticles [2], metal-organic frameworks (MOFs), carbon-based membranes, and geopolymer foams have demonstrated removal efficiencies of up to 98–99% for microplastics [8,9]. However, research on the scalability, field applicability, and cost-effectiveness of these technologies remains limited. Moreover, wastewater originating from livestock and aquaculture not only contains MPs but also carries other pollutants such as antibiotic resistance genes (ARGs), posing a combined risk to environmental and public health [10]. For all these reasons, MP pollution is not merely an environmental issue; it is a global crisis with dimensions of health, economy, and sustainability that must be addressed through a multidisciplinary approach.

MPs are classified into primary and secondary MPs [11]. Primary MPs are micro-sized plastic particles typically used in cosmetics, cleaning products, or industrial applications. They are released directly into the environment during production or use. In contrast, secondary MPs are formed by the breakdown of larger plastic waste over time through physical abrasion, photodegradation by UV light, and various biological interactions. These secondary particles are more prevalent in the environment and may have varying environmental and ecotoxicological impacts due to variations in particle size and surface properties [12]. Numerous studies highlight the widespread presence of secondary MP in diverse ecosystems. For example, studies conducted off the coast of Jember Regency, Indonesia, revealed that MPs detected in marine fish and shells were largely of secondary origin [13]. Similarly, secondary MPs, mostly in particulate form, outnumber primary MPs in sediments of urban wetlands, highlighting their persistence and dispersal characteristics in contaminated environments [14]. Roadside surveys in Nigeria also found that secondary MPs constitute a significant portion of the total microplastic burden, indicating their increasing role in terrestrial environments [15]. In this study, it was determined mostly fragments as secondary MP, and the proportion of fragments was calculated between 67% and 73% for different samples.

The primary objective of this review is to present the sources, environmental distribution, ecological and toxicological effects, treatment technologies, and future sustainable intervention strategies of microplastics from a holistic and interdisciplinary perspective. This paper aims to bridge the gap between scientific understanding and policy-level action by integrating knowledge from environmental science, materials engineering, public health, and industrial practices. Unlike studies that narrowly focus on a single aspect of microplastics, this review synthesizes insights across multiple sectors—such as textiles, packaging, agriculture, construction, energy, and pharmaceuticals—to highlight both the inadvertent emissions and the deliberate industrial uses of microplastics.

2. Microplastics in Sectoral Dispersion and Industrial Applications

2.1. Sectoral Sources of Microplastic Pollution

Microplastics (MPs) are unintentionally released into the environment through production, consumption, and waste processes across various industries, making them a significant global environmental issue. One of the most prominent sources of these particles is the cosmetics and personal care sector. Microbeads used in products such as facial cleansers and toothpaste often escape complete removal in wastewater treatment plants, ultimately entering aquatic environments [16].

The textile industry is another major contributor, particularly through the washing of synthetic fiber-based fabrics, which results in the release of significant amounts of microplastic fibers. These fibers enter wastewater systems and are not fully removed by most conventional treatment processes [7]. Studies have shown that a single wash can release tens of thousands of microplastic fibers from a garment [17].

The packaging and food sectors also pose a direct route for microplastic exposure to human health. Factors such as heat, UV radiation, and mechanical pressure can cause microplastic particles to migrate from packaging materials into food [6].

These particles may then be ingested and pose potential health risks through the human digestive system.

In agriculture, plastic mulch films, bioplastic additives, and components from irrigation systems contribute to the accumulation of microplastics in soil. Long-term accumulation in agricultural fields can disrupt soil microbiota and reduce productivity [4].

The paint and construction industries also play a role in indirect microplastic release into the environment through plastic-based resins, floor coatings, and insulation materials. These materials may fragment during construction waste disposal or through physical degradation, releasing microplastics into the air or leaching into groundwater [1].

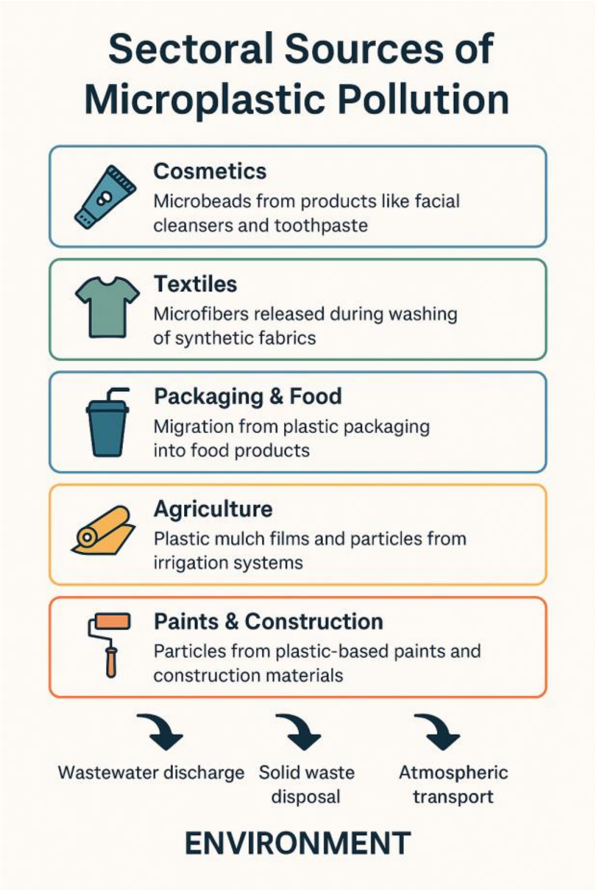

Figure 1. *Sectoral Sources of Microplastic Pollution*

Across all these sectors, the microplastics produced or used are disseminated into the environment via wastewater discharge, solid waste disposal, and atmospheric transport, leading to persistent contamination in ecosystems [5].

2.2. Industrial Applications of Microplastics

Microplastics are not only environmental threats but also versatile synthetic materials that are deliberately utilized across many industrial sectors. Polymer-based microplastics such as polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), and polyethylene terephthalate (PET) are widely employed in industrial applications due to their various physical and chemical advantages [18,19]. However, these applications expose microplastics to environmental conditions that may lead to their degradation and unintentional release, posing potential risks to ecosystems and human health.

The textile industry is one of the primary sectors where microplastics are commonly used. In particular, polymer-based microplastic additives are favored in technical textiles, waterproof garments, workwear, and performance-enhanced fabrics due to their ability to increase durability and abrasion resistance [2]. Yet, the shedding of microplastic fibers during the washing of synthetic fabrics remains one of the most significant sources of microplastic pollution [17].

The construction sector is another major area of use, where microplastic-based polymers are found in composite panels, flooring reinforcements, exterior claddings, and waterproofing membranes. These materials are chosen for their lightweight, elasticity, thermal resistance, and cost-effectiveness, particularly in improving the energy efficiency of buildings [20]. However, physical and chemical weathering of these materials over time results in the release of microplastics into the air and soil [21].

In the energy sector, microplastics are typically considered a secondary resource. The conversion of plastic waste into energy through pyrolysis or gasification plays a key role in waste management and renewable energy production. Additionally, the use of microplastic-laden waste as Refuse-Derived Fuel (RDF) indicates the integration of these materials into energy recovery processes [7].

Filtration and membrane technologies represent advanced engineering applications where microplastics provide beneficial contributions. Polymer-based microplastics are used in filter supports, membrane layers, and selective barriers, enhancing the durability and particulate retention capacity of filtration systems [8]. Nevertheless, the residual microplastics accumulated on filter surfaces may pose secondary pollution risks if not properly managed.

In the food and packaging industries, microplastic-containing materials are widely used to protect, transport, and store products. PET bottles, polystyrene containers, and polypropylene-based packaging may release microplastic particles into food products under conditions such as heat, UV exposure, or mechanical stress [22]. These particles can then be ingested, introducing potential toxicological risks to humans [19].

In medicine and pharmaceuticals, microplastics are commonly used in micro- and nanocarrier systems, especially for targeted drug delivery. These polymer-based particles facilitate the controlled and safe release of active pharmaceutical ingredients [23]. They are also used in surgical sutures, implant coatings, and laboratory disposables. However, the long-term effects of such materials remain unclear, and additives such as bisphenol A (BPA) and phthalates raise concerns about their toxicity [24].

In the automotive industry, microplastics are incorporated into various parts to reduce weight, improve impact resistance, and lower production costs. Bumpers, dashboards, and trim materials often contain polymer-based microplastics that improve fuel efficiency and environmental resilience [25]. However, tire wear particles resulting from road friction are among the most widespread forms of microplastic pollution

[26].

The sports and recreation sector are other fields where microplastics are widely used. Synthetic turf, rubberized running tracks, fitness equipment, and various sports gear are often manufactured using microplastic-based materials [19]. Prolonged use and surface wear can lead to increased exposure, particularly among sensitive populations such as children.

In conclusion, microplastics, though offering functional advantages since the Industrial Revolution, also present substantial environmental and health risks. Their use in industrial applications must be evaluated not only in terms of technical performance but also through the lenses of sustainability, public health, and ecological impact. Therefore, comprehensive environmental risk assessments should be conducted at every stage of microplastic-containing product life cycles—from production to end-of-life. Moreover, the promotion of biodegradable alternatives and the mitigation of environmental contamination from such products are essential for achieving long-term sustainability

2.3. Innovative Approaches and MP Applications

Integrating best practices, innovative approaches, and potential uses of microplastics into studies can significantly increase the scope and depth of research on microplastic pollution. As research on microplastics progresses, management strategies that not only aim to reduce the current pollution burden but also consider innovative applications where these materials can be utilized for environmental and industrial benefits are needed. This two-pronged approach can both lead to the development of workable solutions and enhance the effectiveness of research and policy development, contributing to long-term environmental sustainability goals.

Good practices in data management processes and research methodologies can significantly improve the reliability and overall quality of scientific studies on microplastics. In this context, Jenkins et al. [27] emphasize that sharing data and adopting effective data management approaches in microplastics research foster methodological learning among researchers, thereby improving the consistency of scientific outputs. Similarly, Hung et al. [28] note that rigorous and standardized sampling methods are critical for accurately detecting and assessing microplastics in diverse environmental settings. Such methods enable the generation of robust and comparable datasets to support environmental decision-making. Another study found that uncertainties in the definition, classification, and analysis protocols used in most microplastics studies severely limit the comparability and reproducibility of scientific results. This study emphasizes that disseminating principles such as open data sharing, analysis transparency, and standardized reporting practices are fundamental to microplastics science [29]. On the other hand, one study emphasizes that developing a standardized methodology for microplastic analysis, in line with the European Marine Strategy Framework Directive (MSFD), is critical not only for scientific outcomes but also for policy development [30].

Overall, for microplastic research to achieve higher levels of accuracy, transparency, and comparability, the systematic application of not only good case studies but also robust methodological frameworks and data management strategies is necessary.

3. Treatment and Removal of Microplastics (General Overview)

Microplastics (MPs) are emerging pollutants that pose serious threats to aquatic ecosystems and human health. In recent years, contamination of water resources by MPs has become an increasing concern among environmental scientists. These small plastic particles enter aquatic environments through various pathways, including municipal and industrial wastewater discharges, atmospheric fallout, surface runoff from urban and agricultural areas, and leachate from landfills [31]. Various removal strategies have been developed, including physical processes such as membrane filtration, chemical methods like coagulation–flocculation and advanced oxidation, and biological approaches involving microbial degradation [32-35]. Each technique offers specific advantages depending on the water matrix and the characteristics of the MPs.

Physical methods primarily separate or remove MPs based on differences in size, density, and movement behavior [36]. Among the most effective physical methods are filtration systems, such as sand filters [37] and membrane filtration technologies [38]. Fajar et al. [37] reported that rapid sand filters (RSFs) achieved a 96.6% removal rate for MPs larger than 200 µm. Another study evaluated multiple treatment methods including membrane bioreactors (MBR), disc filters, RSFs, and dissolved air flotation. The removal efficiencies were as follows: 99.9% for MBR (reducing MPs from 6.9 to 0.005 MP/L), 97% for RSFs (from 0.7 to 0.02 MP/L), 95% for dissolved air flotation (from 2.0 to 0.1 MP/L), and 40–98.5% for disc filters (from 0.5–2.0 to 0.03–0.3 MP/L) [39]. A novel gravity-driven dynamic membrane (DM) filtration system was tested by Colakoglu et al. [40] for treating wastewater from plastic recycling facilities. The system achieved over 99.5% MP removal from influent concentrations of 12,835±6218 MP/L. MP removal efficiencies ranged from 68.3% to 99.0% depending on the pore size of the supporting layers. The formation of the DM layer was facilitated by MP fiber networks, resulting in higher removal of fibers compared to fragmented MPs.

In addition to physical methods, chemical treatment approaches such as coagulation, electrocoagulation, and advanced oxidation processes have been extensively studied. Coagulation is one of the most researched chemical methods for MP removal. It involves adding coagulants to wastewater, which aggregate MP particles into larger flocs that can be removed by sedimentation or filtration. Xue et al. [41] demonstrated that using 30 mg/L of alum could remove over 80% of MPs smaller than 25 µm, depending on the alum dose, MP size, and turbidity of the water. In another study, aluminum sulfate was used in coagulation–flocculation processes to remove polyethylene (PE) and expanded polystyrene (EPS) MPs. Removal efficiencies ranged from 87% to 97% depending on aluminum sulfate concentration and pH [42]. Wang et al. [43] found that weathered MPs enhance coagulation efficiency compared to pristine MPs, and that

$FeCl_3$ and polyaluminum chloride (PACl) were significantly more effective than polyferric sulfate, alum, $Al_2(SO_4)_3$, and $FeSO_4$, mainly due to the size of flocs formed during hydrolysis.

In drinking water treatment, Ma et al. [44] observed that although smaller PE particles showed slightly better removal, the efficiency with traditional coagulation remained below 15%. However, when high doses of anionic polyacrylamide (PAM) were added, removal efficiency increased significantly to 90.9%. While both aluminum- and iron-based salts are commonly used as coagulants [45,46], aluminum-based coagulants may leave residual aluminum in treated water, posing potential health risks such as neurotoxicity [47]. Conversely, iron-based flocs tend to settle more effectively due to their higher density [44].

Another crucial system for MP removal is wastewater treatment plants (WWTPs). Although WWTPs are capable of removing a significant portion of MPs, they are still identified as point sources of microplastic pollution [48-50]. For instance, Long et al. [51] reported that MP concentrations dropped from 1.57–13.69 items/L at the inlet to 0.20–1.73 items/L at the outlet, resulting in removal efficiencies between 79.3% and 97.8%. Nevertheless, due to the daily discharge volume, it was estimated that approximately 6.5×10^8 MPs are released into Xiamen Bay every day. Similarly, Gies et al. [52] reported that although 97–99% of MPs were removed at Vancouver's largest WWTP, approximately 30 billion particles were still discharged annually into receiving waters. On average, primary and secondary treatment stages achieve 78–98% and 7–20% MP removal efficiencies, respectively [53,54]. Bayo et al. [55] found that MP removal varied by polymer type, with a maximum removal rate of 90.3%. Edo et al. [56] identified twelve types of anthropogenic polymers in the effluents and sludge of a WWTP, including PE, PP, polyester, and acrylic fibers. Despite removing over 90% of MPs, the plant was estimated to release around 300 million particles daily. Sludge mismanagement could release up to 10^{13} particles into soil annually, raising serious concerns about land application of biosolids.

4. Future Outlook

Microplastic pollution is projected to become a central issue not only in environmental sciences but also in fields such as public health, toxicology, food safety, water management, policy studies, and climate change mitigation. Current trends indicate that MPs are pervasive not only in aquatic systems but also in soil, the atmosphere, and even the human body—making them a virtually inescapable, lifelong exposure source. These particles can carry chemical contaminants and biological agents that may cause genotoxicity, inflammation, hormonal disruption, and immune system impairments in living organisms. Particularly concerning is the emerging evidence that nanoplastics (NPs)—MPs broken down into nanoscale fragments—can cross the blood-brain barrier, posing serious neurological risks and necessitating new toxicological research.

Ecologically, the accumulation of MPs in food webs—especially in higher trophic level species—leads to toxic cumulative effects that threaten biodiversity in aquatic systems. MPs have also been found to interfere with the global carbon cycle and oceanic carbon sequestration capacity, thereby undermining the climate-regulating function of marine ecosystems. This suggests that plastic pollution indirectly contributes to climate change. Although advanced technologies such as magnetic nanoparticles, metal-organic framework (MOF) membranes, geopolymer foams, and biofiltration systems promise high removal efficiencies, challenges remain regarding energy consumption, cost-effectiveness, field applicability, and efficacy against multiple contaminants. Future systems are expected to target not only MPs but also co-contaminants such as antibiotic resistance genes, pharmaceutical residues, and heavy metals.

On the policy front, a paradigm shift in microplastic regulation is anticipated. Initiatives like the European Green Deal and the United Nations Global Plastic Treaty point toward binding international frameworks that limit MP emissions and increase producer accountability. New policies may include mandatory labeling, sustainable production standards, and the implementation of extended producer responsibility (EPR). In parallel, cutting-edge biotechnological solutions—such as synthetic biology, enzymatic biodegradation, and AI-assisted monitoring—are poised to revolutionize microplastic detection and degradation. Enzymes like PETase and MHETase are enhancing the biodegradability of plastics in natural environments, while genetically engineered microorganisms are gaining traction as viable solutions.

In light of these developments, microplastic pollution is no longer just an environmental issue but a multidimensional crisis that intersects with public health, sustainable development, and climate governance. Accordingly, mitigation strategies must be not only technically sound but also ethically, economically, and socio-politically integrated. Combatting microplastics may become one of the most invisible yet widespread environmental challenges of the 21st century

5. Conclusions

This paper presents a comprehensive review of recent studies addressing the growing global concern of microplastics and their management. The findings indicate that microplastic pollution is not merely an environmental issue but a multidimensional crisis impacting public health, food safety, ecological stability, and economic sustainability. Therefore, solution strategies must be interdisciplinary, multi-scaled, and prevention-oriented. Tackling microplastic pollution requires not only advanced treatment technologies but also policy reform, producer responsibility, and societal behavioral change. The integrative perspective provided by this study aims to inform future research, practical applications, and policymaking processes.

- Microplastics are now widely found in soil, water, air, and the food chain, reaching humans and animals through bioaccumulation and biomagnification. Accordingly, monitoring systems must be expanded, and regular analyses of microplastics in drinking water, food, and environmental media should be implemented. Conventional treatment systems are inadequate for removing micro- and nano plastics, particularly those smaller than 100 µm. High-efficiency, integrated treatment approaches based on advanced technologies—such as magnetic nanoparticles, metal-organic frameworks (MOFs), and geopolymer foams—should be developed to ensure more effective removal.

- Microplastics function not only as physical pollutants but also as toxic vectors that transport pesticides, heavy metals, and antibiotic residues. Therefore, treatment systems must be designed to target multiple contaminants simultaneously, ensuring that both MPs and co-pollutants are removed together.
- Antibiotic resistance genes (ARGs) are increasingly found alongside microplastics in livestock and aquaculture waste. This calls for the development of sector-specific treatment approaches that integrate biological, chemical, and physical methods tailored to agricultural and livestock systems.
- Microplastics are known to disrupt carbon cycling in aquatic ecosystems, thereby weakening natural climate-regulating functions. Ecosystem-based research programs should be supported to monitor the impact of MPs on carbon sequestration and phytoplankton health.
- The long-term health impacts of microplastics remain unclear, including their potential roles in neurotoxicity, endocrine disruption, and genetic alterations. Longitudinal, clinical, and epigenetic toxicological studies—particularly those focusing on children and vulnerable populations—must be conducted to clarify exposure risks.
- Most polymers used in plastic production have a high potential to generate microplastics in the environment. Research and development should be prioritized to identify biodegradable and environmentally friendly alternatives to widely used polymers such as PET, PS, and PVC. However, the possible adverse impacts of biodegradable plastics must also be critically evaluated.
- In many countries, clear policies and binding legal frameworks for combating microplastic pollution are lacking. Models such as Extended Producer Responsibility (EPR) should be adopted, and binding international agreements limiting microplastic emissions must be urgently implemented.
- Public awareness regarding the dangers of microplastics remains low, and individual behaviors often exacerbate environmental burdens. Educational initiatives and awareness campaigns targeting schools, media outlets, and community platforms should be widely disseminated.
- Given the complex and cross-cutting nature of microplastic pollution, single-discipline solutions are insufficient. Multidisciplinary and holistic strategies—integrating environmental engineering, medicine, biology, policy science, and economics—must be developed. The insights of the academic community should be actively considered by policymakers to shape more effective and inclusive solutions.

Authors Contributions

Literature research - AÖ, AY, BK; Writing – original draft - AÖ, AY, BK; Review & editing – AÖ, AY

Conflict of Interest Statement

The authors declare that there is no conflict of interest regarding the publication of this paper.

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