Microplastics in aquatic ecosystems: sources, impacts, and mitigation strategies

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Abstract

Aquatic ecosystems serve as one of the ultimate repositories for microplastics (MP). The present article employed a systematic and narrative study method to recognize and summarize advancements, deficiencies, and prospective directions in MP surveillance research within the Turkish aquatic ecosystem and its resident aquatic animals. A collection of 60 peer-reviewed papers listed on Web of Science was included in the systematic examination. The present condition of MP contamination in aquatic settings, encompassing marine and freshwater habitats, aquatic life, and the origins and features of MPs, was examined narratively. The stance on the international plastic pact and mitigation strategies was discussed. Despite a noted rise in publication volume over time, the quantity and scope of research conducted in aquatic ecosystems remain constrained. Stringent regulations must be implemented and enforced to address plastic contamination. Comprehensive long-term monitoring investigations in aquatic habitats should be undertaken periodically nationwide.

Keywords: Microplastics, Aquatic ecosystems, Mitigation, Impacts, Sources

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Introduction

Since its inception over a century ago, plastic has become an essential element of our daily existence (Rangel-Buitrago *et al.*, 2024). Plastics are utilized in nearly all industries, such as chemicals, power, automobiles, defense, aerospace, shipping, logistics, construction, tourism, wrapping, and agriculture, owing to their numerous advantageous properties, such as adaptability, resilience, resistance to corrosion, low density, and minimal electricity and heating conductivity (Salami *et al.*, 2024). Global yearly plastic production increased from 1.8 million tons in 1960 to over 450 million tons in 2020. Nearly fifty percent of these manufactured plastics infiltrate the natural world, impacting all tiers of the ecosystem (aquatic, terrestrial, and atmospheric) due to insufficient waste disposal (Fadaei *et al.*, 2024).

The use of plastic, which is extensively widespread, currently counts among the foremost global environmental problems (Kumar *et al.*, 2021). The primary concern regarding these substances, which possess vast and significant applications, is their disposal after use. Pollution from plastic has emerged as an international concern for the environment and human health, attributed to inadequate breakdown due to excessive manufacturing, utilization, and disposal.

Plastic contaminants can be categorized into many classes according to their dimensions: megaplastics (>120 cm), macroplastics (20 mm- 120 cm), mesoplastics (5-20 mm), microplastics (MP) (0.5 µm-5 mm), & nanoplastics (<0.5 µm). MPs can be classified as primary or secondary based on their initial form. The main types of MPs denote plastics manufactured directly as microparticles, predominantly linked to the healthcare and pharmaceutical sectors, and encompass various particle forms, such as fibers, pieces, films, spheres, and granules (Kılıç, Yücel and Turan, 2022). Additional MPs result from the progressive fragmentation or breakdown of pre-existing larger plastics in the atmosphere.

Decomposition occurs via multiple mechanisms, including hydrolysis in aqueous environments, the photodegradation induced by ultraviolet radiation, weathering from contact in sediments or dirt, oxidation from heat, wave action, and decay caused by microorganisms (Meng *et al.*, 2022). Plastic particles can be further classified according to their physical characteristics, including shape, color, and size.

MPs demonstrate extended ecological durability, leading researchers to thoroughly examine their behavior throughout diverse ecosystems, including living organisms (Vimalkumar *et al.*, 2022). The persistent presence of MPs highlights their possible effects on the environment and human well-being. MPs comprise a heterogeneous array of particles that tend to adsorb deleterious contaminants.

Given these urgent concerns, it is essential to comprehend the magnitude of MP contamination in Turkish maritime habitats. Determining the origins, routes, and effects of MPs on aquatic organisms is necessary for executing successful methods for mitigation and conservation efforts. By confronting this issue directly, the research can restore the natural splendor of these beaches and protect the abundant wildlife within these waters (Deshmukh and Nair, 2024). The rise in plastic debris has become a critical global ecological problem, crossing borders and affecting aquatic environments globally (Mihai *et al.*, 2021). Noted for its abundant marine life and essential water supplies, MP contamination presents considerable consequences for the ecosystem and human well-being. This analysis examines the intricacies of MP contamination in Turkish maritime environments, investigating its sources, shipping, and possible effects on the ecosystem and marine life (Cassavia *et al.*, 2022).

Methodology

A search for publications in the Scopus repository for "MPs" in the "title, abstract, or keywords," released from 1960 to 2025, yielded 6000 items. No changes in annual publishing output were noted before 2015, with fewer than five papers produced annually before 1970 and fewer than 30 until 2015 (Figure 1). For this summary, articles addressing sources of MPs, the processes that govern MP development, the fate and actions of MPs in ecosystems, their adverse health effects, and treatment options were chosen based on their titles, abstracts, and phrases. A higher priority was placed on the most recent publications from 2015 to 2025 to tackle contemporary scientific study findings about MPs. The researchers assert that this review is crucial for developing and exploring superior methods for the cleanup of MPs in the future.

Processes of MP Synthesis

Once created, MPs are conveyed through sewage runoff and infiltrate municipal pollutants, clean water, or marine systems (Österlund *et al.*, 2023). Due to their dimensions, these particulates evade traditional water filtering processes and enter waterways, posing a possible danger to aquatic and human beings. Second-generation MPs are generated from the fragmentation of larger plastic items, resulting from pollution, cracking, and deterioration caused by elements, biological factors, and ultraviolet exposure. The polymers are further disintegrated by the abrasive action of waves upon the beach stones and sand (Deshmukh and Nair, 2024).

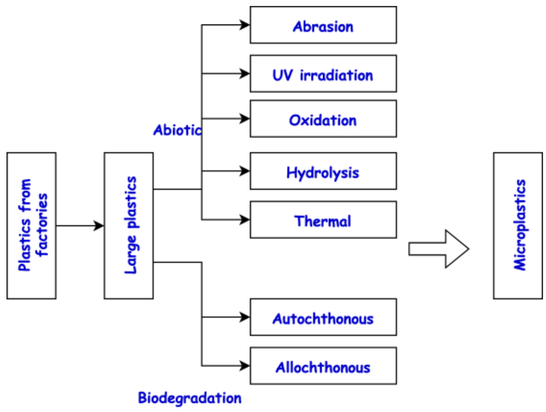

Figure 1: MP process.

Abiotic degradation refers to how polymers are broken down into MPs through physical and chemical forces. The primary mechanisms leading to the abiotic deterioration of plastics include irradiation, oxidation, heat effects, breakdown, and abrasion caused by waves in marine environments. The most prevalent polymers are non-biodegradable; they collect in the natural world. Biodegradation of polymers typically transpires in both marine and desert ecosystems (Dhanraj, Hatha and Jisha, 2022). Biodegradation levels are minimal in aquatic settings, especially at the bottom level. This is primarily due to the reduced population of microorganisms in these conditions. In shallow oceans, diverse microbe populations play a vital role in biodegradation (Nabi *et al.,* 2023) The biotic breakdown of polymers is a complex process that necessitates the involvement of multiple species of microbes for thorough breakdown into MPs (John and Ghate, 2024).

Fundamental Attributes of MPs in Marine Organisms

In aquatic habitats, MPs and their associated compounds can infiltrate creatures by several mechanisms: (i) absorption via gills, (ii) absorption through eating, and (iii) direct attachment to species. Colors are believed to enhance the selective characteristics of MP fragments in animals. Fish demonstrated a predilection for MP pieces in black and blue dyes. This could be ascribed to the greater incidence of black and blue hues in aquatic settings.

Diverse processes and methodologies can evaluate the quantification of MPs consumed by fish. The administration of 10% potassium hydroxide (KOH) solutions for digesting biological material in the gastrointestinal system is standard. Due to their corrosive nature, employing many acid solutions diminishes **the** recuperation rate of most plastics. The two prevalent techniques for isolating MPs in organic materials are the use of KOH and the use of hydrogen peroxide (H2O2). Reports indicate that H2O2 levels of ≥25% degrade specific polymers, while an 18% H2O2 solution causes negligible alterations to the polymer spectrum (Mariani and Malucelli, 2023). MPs vary in chemical makeup, density, form, and particle size. These characteristics affect MPs' behavior, trajectory, and movement inside the medium.

The analysis of MPs requires efficient and rapid analysis methods, typically comprising two phases: the digestion of the biological element and the identification, evaluation, and measurement of MPs. Diverse analytical methodologies have been employed to assess MPs from multiple perspectives. Moreover, this is not exhaustive, indicating that many methods must be used to provide a complete understanding of MP qualities, particularly when assessing MP activities. Methods capable of identifying MP structural changes, utilizing chromatography and spectral analysis, are more advantageous than those primarily focused on surface and morphological changes through microscopy techniques.

In marine and freshwater research analysis, fiber MPs are considered prominent, with potential sources including laundry, urban garbage, and wastewater releases. As time passes, the significant presence of cellulose, coupled with other variables (actual, chemical in nature, and biological), results in significantly smaller nanoparticles. The size and placement of the MPs extracted from the examined species varied between the experiments. MPs of various size classifications were detected in organisms from aquatic habitats. Significant discrepancies were seen in the size distributions of MPs, with a rise in MP counts corresponding to a drop in particle size. Fish deliberately or inadvertently eat microscopic MPs, but larger particles don't survive in their intestinal tracts after consumption and are expelled in feces.

MPs in Environmental Compartments

Notwithstanding several investigations on MPs, their environmental fate remains inadequately comprehended. Multiple studies have demonstrated that MPs are susceptible to degradation and readily disseminate indoors and outdoors. Owing to the hydrophobic characteristics of MP things, they can markedly adsorb harmful organic substances and are regarded as carriers for most Persistent Organic Pollutants (POPs) enumerated in the Stockholm Protocol. Plastics are more likely to function as passive samplers than vectors for POPs. MPs can serve as vectors for bacteria. Future research should focus on transmitting hazardous chemicals via MPs to living beings and the infections they carry. The transit and fate of MPs are primarily governed by their chemical and physical characteristics and the surroundings in which they exist. A comprehensive examination of these aspects warrants additional research.

The diminutive dimensions of MPs and their low weight enable them to remain airborne and be readily inhaled, posing health hazards. Fibers constitute a prevalent and substantial contributor to MPs in maritime and atmospheric environments, and their ingestion result in a discharge of numerous contaminants within living creatures. A thermodynamic approach for assessing the ambient contact of chemical adsorption on MPs indicated a minimal importance of MPs as a carrier for constant, bio-accumulative toxins compared to alternative exposure paths. However, as noted by the investigators, this investigation was constrained by insufficient data on motion, chemical reactions (desorption and absorption), the impact of microbial biofouling, and the evaluation of MP fate within microorganisms to enhance comprehension.

To successfully handle MPs and mitigate their adverse ecological effects, it is essential to comprehend their sources, fate, and environmental behavior. The subsequent sections offer a concise overview of the principles behind MP production, how they act, and their fate across different environments.

Aquatic Ecosystem

The placement of MPs in waterways is affected by multiple dynamics, notably fouling and density, which in turn dictate their effects on marine life. Following fragmentation, less dense MPs remain buoyant on the water's surface, but more dense MPs descend and settle in the sediments. MPs are exchanged among biota, fluid, and sediment via fermentation, ingestion, and urine. The influx of freshwater and its turmoil can mix or disrupt MPs in marine environments, resulting in their relocation. A recent modeling study on plastic particle transport demonstrated that river fluid dynamics significantly affect stream MP dispersion and their entry into aquatic environments.

Pedology and Alluvium

Although MP pollution in marine ecosystems is well recognized, research on the prevalence and detrimental impacts of MPs in soil remains limited. Due to the hazardous compounds integrated during production, MPs adversely affect soil environments, flora, and fauna. A recent assessment evaluating soil degradation by MPs concluded that pollution levels were comparable to those of dangerous metals. Wastewater sludge is an essential contributor of MPs to the soil. Notwithstanding poisonous compounds in MPs and their significant adsorption capacity for deleterious contaminants from nearby surroundings, sewage waste is frequently utilized as a fertilizer. 50% of the effluent from municipal treatment plants is used in agricultural lands. This indicates that farms treated with sewage sludge serve as potential storage areas for MPs. A new study suggests that Earth's microarthropods facilitate forming and disseminating surface-deposited plastic particles inside the soil food web. Comprehensive research in this domain is insufficient. Urgent studies and thorough examination are necessary to mitigate the impacts of plastic particles on terrestrial ecosystems.

MPs in sands have been extensively documented worldwide. Research conducted on the East Frisian Islands shoreline indicated elevated MPs concentrations in fine-grained sand. In many instances, diminutive plastic particles and seawater infused with MP fibers infiltrate coastal debris, elevating the concentration of MPs inside the rock. Other investigations revealed elevated concentrations of MPs in materials collected from the same venue. 25-35% (w/w) MPs were observed in sediment specimens from Edgbaston Pools in the UK.

In contrast, the Changjiang River recorded a median of 120 ± 5 per kg of dry-weighed particles. High amounts of MPs were similarly identified in the sandy sands of the northwestern Mediterranean Sea along Namibia's west-eastern shoreline. Work on identifying and quantifying MPs in soils demonstrates that soils serve as a primary reservoir for MPs. The mechanisms by which MPs descend into debris, whether through physical or biological means, necessitate a thorough investigation.

Interactions of MPs with Contaminants

MPs can adsorb most organic contaminants and harmful metals in the natural world. As a result, they serve as vectors for hazardous materials such as pesticides, synthetic biphenyls, and hydrocarbons that are polycyclic aromatic hydrocarbons. Organic contaminants are notably resistant to biochemical, chemical, and photocatalytic destruction.

The consumption of MPs, on which these poisonous substances attach, exposes creatures and people to harmful chemicals. The buildup of hazardous metals like cadmium, nickel, lead, and zinc has been documented. The research project examined the impact of MPs on the absorption of dangerous metals in rainwater, revealing that MPs serve as vectors for transmitting hazardous metals between urban environments and water resources. MPs' ability to scavenge hazardous compounds is primarily due to their diminutive size and hydrophilic characteristics.

MPs harbor toxic chemicals incorporated during production to mitigate fire hazards, and ultraviolet (UV) stabilizers to impede destruction upon exposure to direct sunlight. Chemicals without chemical connection to polymer atoms can be readily liberated from polymers and transported to water, particles, and living beings. The consumption of MPs by marine microbes, animals, and people leads to physical and chemical consequences. MPs' physicochemical properties, including their dimensions, density, and chemical structure, are critical factors influencing their availability to organisms. Marine creatures ingesting pollutant-laden MPs adversely affect their eco-physiological activities and significantly disrupt the aquatic food chain.

Strategies for Rehabilitation

Various technologies, including traditional wastewater treatment processes, can be employed to mitigate MP contamination, particularly in aquatic environments. A comprehensive elucidation of these and additional methodologies is included in a recent assessment. An effective remediation plan must acknowledge several challenges related to the MP issue, primarily introducing and retaining plastic in the atmosphere. The problem of MPs is that they are a byproduct of plastics, and the linear methodology regarding the manufacturing, use, and waste of plastics within the economic lifetime. A recent assessment on plastics indicated that the worldwide capacity for manufacturing plastic that degrades is about 4 Mt. This offers a chance to advocate for creating these potentially environmentally friendly products. Examples of readily accessible recyclable plastics that substitute for conventional plastics across multiple uses include polylactide and polyhydroxyalkanoates.

This grim perspective necessitates immediate measures to mitigate the ecological threat posed by MPs. The Microbeads-Free Waterways Act prohibited the use of tiny plastic beads in personal care items in the United States. The Sustainability Authority has banned the manufacture of expanded polystyrene due to its propensity to obstruct gutters and its health hazards. After comprehensive research, producing thin-film polymers for baggage carriers was forbidden. While this series of legislative measures results in transient job and economic losses, they represent constructive initiatives to prevent further degradation of aquatic ecosystems, necessitating global support. Although plastic recycling processes have been well-established in wealthier nations, underdeveloped countries typically lack legal backing, resulting in their implementation and enforcement occurring ad hoc manner.

Naturally biodegradable substances like powdered almonds, pumice stone, and oats have historically been exfoliants in facial cosmetic products. Therefore, a full return to these materials remains a plausible alternative. A report from the House of Representatives indicates that most private corporations have pledged to eliminate the use of tiny beads by 2023, a laudable initiative requiring more incentivization. The presence of MPs in food items like commercial salt from the sea poses potential direct health risks to humans and necessitates control. These solutions can be applied to other aquatic goods vulnerable to MP buildup.

There is a recognition that addressing the contamination of MPs requires re-engineering the manufacturing processes and modifying plastic use throughout the value chains. Understanding MP contamination ideally parallels the public recognition of environmental challenges. Due to the limited awareness indicated by a mere 28% participation rate in a recent poll, engaging all stakeholders to enhance understanding is crucial for abatement and containment measures. Cooperation among various groups can facilitate the establishment of platforms for confinement and reduction. These efforts have united the strengths of laws, research, and regulatory bodies to establish procedures for detecting MPs in water for consumption.

Guidelines for Mitigating MP Pollution in Aquatic Systems

Studies on tracking MP contamination and its effects on aquatic ecosystems are proliferating. To successfully tackle the problem, studies must prioritize bridging gaps in knowledge. Upon reviewing MP research, certain deficiencies and suggestions are apparent:

- Many studies are constrained in scope, frequently concentrating on singular timeframes, resulting in redundancy and overlap. A few studies focus on modeling, prevention, and establishing long-term trends. Although pertinent ministries monitor research, the sample points are insufficient and limited. Therefore, monitoring important ecosystems (such as lakes, national parks, protected waters, etc.) is essential to identify temporal changes in MP contamination. This method can promote the formulation of preventive measures.

- Enhanced collaboration among institutions will facilitate spatially broad investigations and establish standardized methodologies to track MPs in aquatic settings.

- The lack of research pinpointing the origins of MP pollution hinders the development of preventive strategies. The formulation of a national action strategy is essential. This plan will specify MP pollution by sector based on outcomes, facilitating the development of effective preventive initiatives.

- Despite global legal reforms aimed at addressing MP avoidance at its source, the absence of parallel actions exacerbates the environmental issue and amplifies its issues.

- Due to the reported elevated levels of MP contamination along Adriatic and Black Sea beaches and interior waters, it is imperative to implement actions to eradicate the main contributors of MPs. The nation is an applicant for full European Union (EU) admission and endeavors to harmonize its national legislation with EU standards. The EU accession process requires prospective nations to incorporate the EU acquis into their national legal systems and create the managerial and legal frameworks necessary to implement harmonized legislation. Implementing these strategies enables an improved approach to the problem of MP pollution of waterways. Moreover, mitigating unlawful waste disposal activities and establishing national waste management systems are essential to tackle challenges like plastic trash imports.

- The EU Green Budget and the circular economy Action Plan exemplify the European Commission's dedication to addressing the problem of MP pollution. As articulated in the Zero Contamination Action Plan, the Commission intends to diminish MP contamination by 32% by 2035.

This article's analyzed studies indicate that it is at significant risk of MP contamination; therefore, it should implement pollution prevention initiatives in all three-time frames, similar to the EUs. It should enact regulations akin to the EUs to restrict the manufacturing and utilization of purposefully added MPs (such as tiny beads, glitter, synthetic grass, etc.).

- By strengthening its position inside the UN Plastics Treaty structure, adopting regional management, and actively protecting its adjacent seas, it significantly contributes to mitigating MP pollution. Over time, authorities should examine the assessment of health risks associated with MPs in shellfish. Currently, numerous industrialized countries have implemented laws banning the inclusion of plastic microbeads in household items. These rules are essential for alleviating the issue of plastic pollution. The governing body is responsible for supervising the manufacturing, use, recycling, and disposal of plastics to prevent complications and challenges that compromise efforts against MP pollution.

Strict compliance with the concepts of "extended consumer accountability" and the "polluter pays concept" is essential to improve the effectiveness of plastic recovery. The consumption of macro- and microplastics can adversely affect aquatic flora and fauna. Therefore, it is necessary to reduce plastic usage and encourage recycling initiatives. Regulatory initiatives designed to mitigate MP pollution are vital for maintaining ecosystems. Understanding the reactions of global plastic pollution in aquatic ecosystems at various levels will enhance knowledge of MPs and improve the correlation between testing contact studies and real ambient levels, thereby aiding in preserving food security and protecting the environment. Using uniform research methodologies in this context will enhance the economic worth of seafood and fish and promote human wellness.

Conclusion

The research indicates that MPs represent a significant environmental issue for nearly all aquatic habitats, similar to the global situation. Multiple research studies on plastic pollution in marine environments continually underscore the necessity of efficient plastic waste management, awareness-raising, and initiatives to mitigate effects, all of which facilitate the sustainable utilization of plastic items. The results from MP characteristics can indicate probable sources of MPs in marine ecosystems; it is crucial to acknowledge that the relevance of these findings is restricted to natural settings. Pioneering research on the long-term trajectories of MP transportation and pollution should be pursued. Modeling such trajectories enhances our understanding of their motion trends, facilitating more precise analysis.

The ubiquity of these contaminants in all elements of the aquatic environment, their transference across trophic levels, and their influence on the contamination from initial components or handles in various fresh, handled, and semi-processed products, particularly those intended for consumption by people, necessitate vigilant monitoring. Considering the data from a literature review, employing a comprehensive modeling method to simulate plastic particle migration and elucidating the intricate relationships between different variables would substantially improve food safety information and deal with a critical deficiency in the relevant data repository. Understanding of this issue must be heightened, and more rigorous research should be conducted to safeguard the natural world and the health of humans.

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