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Original Article

Investigation of the Sources, Ecological Impacts, and Removal Strategies of Microplastics in Aquatic Environments

Hafez Ajam Ekrami[1], Fatemeh Kiani[1*], Mohammad Javad Mohammadi[2,3], Sima Tahmasi[1], Maryam Hormati[1], Masoume Taherian[1]

[1] Student Research Committee, Department of Environmental Health Engineering, School of Public Health, Ahvaz Jundishapur University of Medical Sciences, Ahvaz, Iran
[2] Environmental Technologies Research Center, Medical Basic Sciences Research Institute, Ahvaz Jundishapur University of Medical Sciences, Ahvaz, Iran
[3] Air Pollution and Respiratory Diseases Research Center, Medical Basic Sciences Research Institute, Ahvaz Jundishapur University of Medical Sciences, Ahvaz, Iran

Abstract

Background & Aims: Microplastics (MPs) have become a significant environmental pollutant, posing serious threats to aquatic ecosystems. The present study aimed to comprehensively examine the characteristics, sources, environmental impacts, and removal strategies of MPs in aquatic environments.

Materials and Methods: A narrative review was conducted through a systematic search across Scopus, PubMed, Google Scholar, and Web of Science, focusing on articles published between 2013 and 2024. Keywords related to microplastics, aquatic organisms, and removal methods were applied. After screening 729 retrieved articles, 56 relevant studies were selected for analysis.

Results: Microplastics originate from both primary and secondary sources, entering aquatic systems through industrial discharges, wastewater treatment plants, surface runoff, landfill leachate, and atmospheric deposition. Due to their persistence and small size, MPs are widely distributed and tend to accumulate in aquatic organisms. This accumulation can lead to various harmful physical and chemical effects, including oxidative stress, immune suppression, neurotoxicity, reduced nutrient absorption, and potential biomagnification through the food chain. To mitigate MP pollution, various removal methods have been investigated. These methods include physical approaches, such as membrane filtration, chemical treatments (e.g., advanced oxidation processes), and emerging biological methods utilizing biochar and biomaterials. Research suggests that combining different technologies can enhance removal efficiency, while biomaterials, due to their greater environmental compatibility, offer particularly promising strategies.

Conclusion: Combining technological approaches appears to improve the efficiency of microplastic removal, with biomaterials showing notable potential due to their environmental compatibility. However, it is essential to evaluate the effects and effectiveness of these methods from different technological and ecological perspectives.

Keywords: Methods, Microplastics, Removal, Water resources

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1. Introduction

Plastics are among the emerging dangerous pollutants in the world. According to the report of Plastics Europe (2018), its production is growing exponentially, probably reaching more than the number of sea fish by 2050, up from 350 tons in 2017 [1, 2]. Based on their size, plastics in the environment include megaplastics (>50 cm), macroplastics (>5 to 50 cm), mesoplastics (5 mm to 5 cm), microplastics (1 µm to < 5 mm), and nanoplastics (<1 µm) [3, 4]. Over the years, the growing use and improper recycling of plastic have significantly increased the presence of this pollutant in all environmental matrices, and it is commonly found in surface water, soil, sediments, and living organisms. According to the report of the United Nations Environment Community, there are about 18,000 plastic pollutants/km^2 floating on the surface of the oceans. If we consider polluted marine areas, the amount of pollution can reach 38,000 plastic pollutants per square kilometer [5-8]. According to the type of polymers, the density and color of MPs varies. About 16.5% of MPs floating on the surface of the ocean are polypropylene, and 54.5% are polyethylene; the rest include polystyrene, polyvinyl chloride, polyamide, and polyester. On the other hand, high-density MPs sink and affect the sea floor [9, 10]. Microplastics are mainly divided into two categories of primary and secondary MPs [11]. Items manufactured in small dimensions and utilized directly for the fabrication of other products are classified as primary microplastics, while those generated from the degradation of bigger plastic objects are

*Corresponding Author: Fatemeh Kiani, Email Address: nazaninfatykian@gmail.com

categorized as secondary MPs [12]. Primary and secondary MPs enter aquatic ecosystems through different pathways. These include: 1) terrestrial items that decompose into secondary MPs and are transported to the ocean by precipitation or wind; 2) larger items discarded on land that are washed into the sea by rain and wind and become secondary MPs in the aquatic environment; 3) primary MPs that are inadvertently released during production, transit, and subsequent utilization, which then enter the waste stream; and 4) entering from sewage treatment plants, which itself takes place in various ways: A) they are discharged into waterways through treated sewage; B) via sewage sludge utilized as agricultural fertilizers and other purposes; and C) through the degradation of plastic components used in urban sewage treatment facilities [12]. Microplastics are ingested by terrestrial and aquatic animals such as crustaceans, zooplankton, fish, turtles, birds, and mammals [13, 14]. Additionally, MPs may have increased toxicity by absorbing substances such as heavy metals, polycyclic aromatic hydrocarbons (PAHs), and pathogens. Microplastics are likely to cause damage to aquatic species by reducing nutrient absorption and oxidative stress, suffocation, and movement restriction [15]. Although not all the facts are fully known, the overwhelming evidence suggests that the consequences of discharging these substances into the environment can be catastrophic. Because plastic waste is very persistent and generally requires more time to degrade. There is a fear that these microparticles and their toxins could be transferred through the food chain to humans through direct ingestion or drinking water [16, 17]. In some studies, water and wastewater treatment with the help of membrane filtration, ultrafiltration, microfiltration, reverse osmosis, coagulation, electrostatic, and chemical oxidation with combined Fenton was reported to be effective in removing microplastic particles [14,18-21]. However, there are many concerns about the increasing number of MPs entering aquatic ecosystems. Therefore, the present study aimed to investigate the origin of these hazardous pollutants until their entrance into water resources, their destructive effects, and to find effective solutions to eliminate or reduce these pollutants.

2. Materials and Methods

In this narrative review, we employed a comprehensive search strategy to explore the relationship between MPs and their impacts on water resources and aquatic organisms. The initial search was conducted in English across several prominent databases, including Scopus, PubMed, Google Scholar, and Web of Science.

2.1. Search Strategy

A search for studies was conducted in the Web of Science, Scopus, and PubMed databases using keywords to ensure comprehensive topic coverage. The search terms included microplastics, MPS, water resources, aquatic organisms, biological methods, membrane filtration, physical methods, and chemical methods. These terms were applied across various fields, such as titles, abstracts, and keywords, to maximize the relevance of the retrieved studies. The search was limited to articles published between 2013 and 2024. A total of 729 articles were retrieved from the aforementioned databases. These articles were then imported into EndNote reference management software for further processing and organization. The inclusion criteria consisted of relevant research articles and articles written in English. Duplicate and non-English articles, and those articles that were unrelated to the topic were excluded from the study. Ultimately, 56 articles were included in the final analysis.

2.2. Ethical Approval

According to national guidelines, this type of study does not require individual consent. The study focused on the analysis of secondary data from publicly available articles and did not involve direct interaction with human participants.

3. Results and Discussion

3.1. Characteristics of Microplastics

Plastic materials are different in terms of properties such as elasticity, hardness, and moldability (Figure 1). The type of linear or branched molecular bond divides them into three categories: thermoset, elastomer, and thermoplastic [22]. The two categories of thermoplastics, semi-crystalline and amorphous, are linear or slightly branched. Hardness and brittleness increase with the increase in semicrystals. Polyethylene, polypropylene, polystyrene, polyamide, polybutylene terephthalate, and polycarbonate are types of thermoplastics. Thermoplastic products include drinking bottles, sports equipment, toys, shampoo bottles, dishes, and bulletproof vests. Thermostats are very resistant to heat and have strong covalent bonds [23]. Vinyl esters, urea formaldehyde, polyurethane are from this category and are used as electrical and thermal insulation in fabrics, adhesives, and hospital products [24]. Elastomers have a chain structure, insoluble and flexible. They are usually used in the manufacture of sports equipment, toothbrushes, toys, lubricants, medical tubes [25]. Based on the shape, MPs are divided into types of microbead films, microfibers, nurdles, fragments, and foam. Fragments produce micro- and nano-plastics as a result of the decomposition of plastic devices, and their characteristics change, such as reducing thermal resistance and increasing hydrophilicity. These types of plastics are widely dispersed in the environment [26, 27]. Microfibers with a thread-like structure and a diameter of less than 50 micrometers enter the sewer when washing clothes. They are the most common MPs made from textiles and synthetic fibers (nylon, polyester, acrylic) and natural (cotton and linen, wool, silk), cellulose (bamboo, diacetate, triacetate) [28]. Nurdles (mermaid's tears) are balls with a diameter of less than 5 mm, from which all plastic products are produced [29]. Microbeads are another form of microplastic with a size of less than 5 mm, which are used in the manufacture of cosmetics [30]. They are stable in the environment and resistant to biological decomposition; which is why they are considered one of the most dangerous microplastics. Therefore, conventional methods of wastewater treatment are often unable to completely remove them, allowing for their entry into water sources [31].

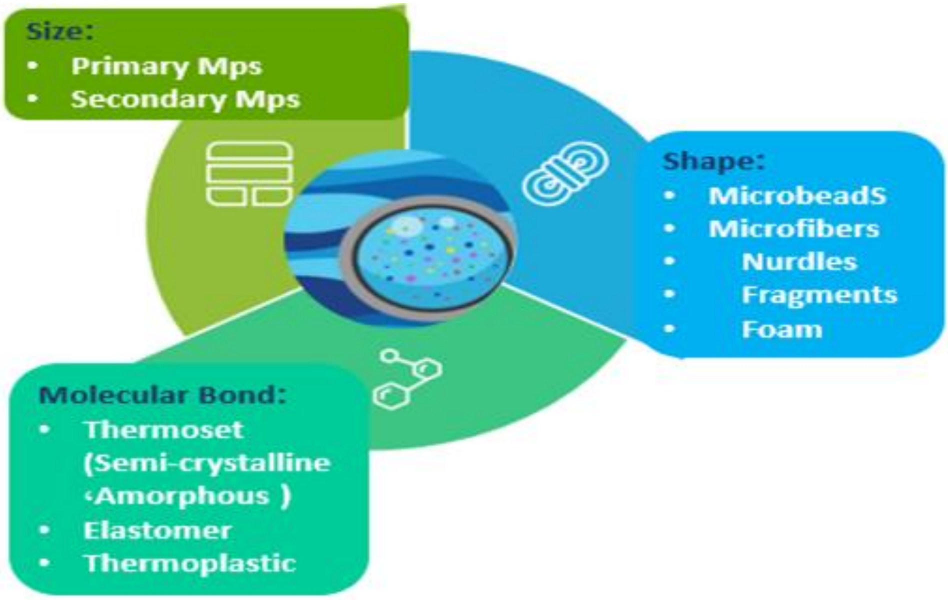

Figure 1. Classification of microplastics

The environmental properties and effects of MPs are closely related to their size, and smaller particles show an increased potential for accumulation in biological tissues. Therefore, we can classify microplastics into primary and secondary MPs based on their size. Primary MPs are particles without weathering and decomposition. Moreover, industries such as hygiene, cosmetics, and textiles, manufacture them on a micro- or nanoscale for specific applications. Their small size (less than 5 mm) makes their effective removal challenging for wastewater treatment facilities, leading to environmental pollution [32, 33]. However, processes such as weathering, sand erosion, UV ray decomposition, hydrolysis, or biological degradation of larger plastics produce secondary MPs. Therefore, there is a change in their roughness, surface, and oxygen content [34].

3.2. Sources of Microplastic Production

According to global production statistics, plastic production increased from 1.5 million tons in 1950 to more than 300 million tons in 2016, and if the increase continues in the future, out of 26 billion tons of plastic waste, 12 billion tons will enter the environment [1, 35]. Microplastics are mainly the result of the breakdown of larger plastic items. Microplastics enter into water sources from different ways and sources (Figure 2). Synthetic clothes release about 700,000 fibers from 6 kg of clothes in one wash [28]. Plastic waste from daily life, including cosmetic products (e.g., scrubbers, toothpaste, and other cosmetics) as a source of pollution can enter aquatic systems [36]. Agricultural or industrial waste [37, 38], medical devices (medical and dental carriers), water and wastewater treatment [39, 40], weathering of plastics [41], floods [42], atmospheric sediment [43], fishing or aquaculture, are among other ways of polluting the water (44). Jinling Ma et al. showed that high levels of MPs from the Pearl River Estuary in China accumulated in the surrounding fish ponds [44]. Microplastics may enter the urban atmosphere through the wear of tires in the movement of cars, sea water spray into the atmosphere, and strong winds, and their concentration can reach from ~1 particle/m^3 to 35 particle/m^3. Airborne MPs may travel long distances, deposit on the ground, and then enter waterways through runoffs. Some of them can directly enter rivers and lakes [43]. Various studies have pointed out a strong correlation between runoff and MP distribution in rivers; for example, after heavy rainfall for two days in a small urban river, the concentration of MP ranged from 400 to 1700 particles/m^3 [45]. On the other hand, runoff due to the lack of urban water management and the overflow of untreated sewage can increase the entry of MP into fresh water. Finally, MPs may find their way from the river to the sea through floods [46]. Another study by Morshedul Haque et al. on sewage and sludge of five different industries, such as pharmaceuticals, printing, dyeing, batteries, and washing, showed high levels of MP pollution through industrial raw materials used and final products [47]. The results of the study by Trihadiningrum et al. (2023) showed that even the MPs of the waste landfill leachate can be considered a source of pollution for surface water [48]. About 80% of freshwater MPs originate from land; they eventually reach the salty waters of seas and oceans. Most of these substances sit on the bottom of the ocean, and a smaller amount of them float on the coastal areas and sea surface [49, 50]. Due to their stability, MPs can remain in the environment for a long time and can be transported to distant areas through a cycle of hydrodynamic factors such as rain, wind, and runoff, leading to their presence even at the poles. According to reports, there are about 18,000 MPs per square kilometer on the surface of the oceans [51, 52].

Figure 2. Pathways of microplastics entering water sources

3.3. Effects of Microplastics on Aquatic Organisms

After entering the environment, MPs may undergo destruction, accumulation in soil, sedimentation on the beach, floating in water, or being swallowed by aquatic organisms [53, 54]. The final destination of MPs infiltrating water is the ocean. About 80% of these MPs residues in aquatic environments are from terrestrial sources and are of the microbeads type [55]. The stability and durability of MPs in different environmental conditions and the presence of other pollutants such as pesticides, dioxins, polycyclic aromatic hydrocarbons (PAHs), Dichlorodiphenyltrichloroethane (DDT), Persistent organic pollutants (POPs), polychlorinated biphenyls (PCBs)on the surface of MPs polymers can aggravate their toxicity [55, 56]. In addition, another reason for MPs toxicity is the presence of additives such as lubricants, dyes, flame retardants, and other substances used to enhance their properties based on their application [57]. The fate of MPs in the aquatic environment depends on their specific gravity. In this way, plastics with a specific gravity higher than seawater (1.02 g/cm2) sit on the seabed and on the surface of the sediments, while particles with a specific gravity lower than seawater remain floating on the surface or in the middle layers of the water [58]. Numerous biological organisms, ranging from single cells to marine mammals, consume MPs due to their diminutive dimensions. In addition to size, the rate of ingestion of plastic particles also depends on their shape, specific gravity, and color [59]. For example, fish and seabirds may ingest Nurdles due to their similarity to fish eggs [60].

Drawing on the data presented in Table 1, it is evident that microplastic pollution poses a significant threat to aquatic ecosystems, with its impacts varying according to polymer type, particle size, and environmental conditions. The evidence indicates that smaller MPs (<5 μm), including polyethylene (PE) and polystyrene (PS), are prone to accumulation in the digestive tissues of aquatic organisms, leading to physiological disturbances such as oxidative stress, immune suppression, and neurotoxicity in species such as *Mytilus galloprovincialis* and *Daphnia magna* [61,62]. In contrast, larger microplastic particles, such as nylon microfibers and polyamide fibers, primarily affect feeding efficiency and digestive processes, compounding the ecological impact [63, 64]. Freshwater and marine organisms respond differently to microplastic exposure. For example, marine species such as *Calanus* helgolandicus tend to ingest chemically infused microplastic particles at a higher rate, while freshwater species such as *Oreochromis* mossambicus experience oxidative stress and DNA damage when exposed to polypropylene [64, 65]. Furthermore, MPs serve as carriers for hazardous contaminants such as pyrene and mercury, which intensify their toxic effects. This can lead to reproductive issues, stunted growth, and metabolic disruptions in affected organisms [61, 66].

Table 1. Overview of the Effects of Microplastics (MPs) on Aquatic Species

Author	Year	MPs Type	MPs Size (µm)	Water Type	Aquatic Species	Key Findings	Observed Effects
Avio. et al [61]	2015	Polyethylene (PE), Polystyrene (PS)	<100	Marine Water	*Mytilus galloprovincialis (Mediterranean mussel)*	MPs adsorbed pyrene and transferred to mussels; accumulation mainly in digestive tissues, causing oxidative stress	Significant effects on immune response, neurotoxicity, and genotoxicity, with marked accumulation in digestive tissues
Blarer. Et al [63]	2016	Polyamide fibers, Polystyrene beads	500Ч20, 1.6	Freshwater	*Gammarus fossarum*	Study on ingestion and egestion; effects on feeding and weight changes	Reduced assimilation efficiency due to polyamide fibers; no uptake of PS beads by gut cells
Heindler. et al [68]	2017	Polyethylene terephthalate (PET)	5-10	Marine Water	*Parvocalanus crassirostris*	Effects on mortality, productivity, population sizes, and gene expression	Reduced egg production and population size; long-term reproductive health effects
Pacheco. et al [69]	2018	Plastic microspheres	1-5	Freshwater	*Daphnia magna*	Chronic exposure study with AuNP and MP; reproductive and developmental effects measured	Increased mortality, delayed brood release, reduced offspring, and synergistic toxicity at high concentrations
Barboza. et al [66]	2018	Fluorescent red polymer microspheres	1-5	Marine Water	*Dicentrarchus labrax (European seabass)*	Investigated toxic effects of MPs and mercury	MPs influenced mercury bioaccumulation; caused neurotoxicity, oxidative stress, and energy metabolism changes
Procter. et al [64]	2019	Nylon microfibers	10Ч30	Marine Water	*Calanus helgolandicus (copepod)*	Enhanced ingestion of DMS-infused MPs compared to non-infused controls	Increased ingestion rates (72%-292% higher); potential risk due to microplastic contamination mimicking prey scent
Huang. et al [62]	2022	Polystyrene (PS)	0.5	Freshwater	*Daphnia magna*	Microplastic exposure impacts reproduction and growth	Delayed sexual maturity, reduced growth rate, and decreased offspring production
Jeyavani. et al [65]	2023	Polypropylene	11.86-44.62	Freshwater	*Oreochromis mossambicus (Tilapia)*	Assessed biochemical, genotoxic, and histological implications	Increased ROS levels, oxidative stress, enzyme activity changes, DNA damage, and liver histological changes
Li. et al [67]	2024	Microfiber, Microplastic pellet	<5 mm	Freshwater	*Chindongo demasoni*	Investigated the effect of swimming behavior on microplastic ingestion	More active fish ingested higher amounts of microplastics; behavioral differences explain variation
Daniel. et al [70]	2024	Polypropylene (PP), Polyethylene terephthalate (PET)	<250	Marine Water	*Mytilus sp.*	Study on ecotoxicological effects of commercial MPs (PP and PET) on mussels	Reduced condition index and feeding rate; no significant metabolic enzyme response; potential long-term ecological impact

The findings also highlight the influence of microplastic exposure on both physiological and behavioral traits of organisms. For instance, more active species are shown to ingest higher quantities of MPs [67]. Prolonged exposure is associated with population declines, reduced reproductive success, and disruptions to ecosystem dynamics [68, 69]. The differential responses observed across taxa underscore the necessity for comprehensive evaluations that consider species specific vulnerabilities, exposure durations, and interactions with environmental pollutants [70].

3.4. Methods of Removing or Reducing Microplastics from Water Sources

Pressure filtration can remove micropollutants that coarse physical filters cannot remove. According to the pore size, these filters are divided into four categories: reverse osmosis (0.1 nm), nanofiltration (about 1 nm), ultrafiltration (1-100 nm), and microfiltration (0.1-10 mm) [71]. Ultrafiltration can effectively remove particles such as proteins, viruses, bacteria, and fatty acids, suspended solids, and even protozoa (e.g., Giardia and Cryptosporidium) [72]. Today, the coagulation process and ultrafiltration are used to remove natural organic matter in water purification. Moreover, several studies have reported the removal of MPs from drinking water with the help of this process. Polyethylene is the most abundant microplastic known in water. The results of a study showed its 91% removal with the help of ultrafiltration in water [73, 74]. However, due to the settling of particles after the use of coagulants, the performance of membrane filters decreases due to membrane sedimentation. Membrane clogging increases the number of cleanings time, consumes more energy, and shortens the lifespan. Reverse osmosis is used by applying high pressure to a concentrated solution to remove pollutants, salts, heavy metals, and other impurities in industrial and urban water purification systems [72, 75]. The results of a study in a treatment plant in Australia showed that the reverse osmosis process after sedimentation, flocculation, and ultrafiltration methods effectively reduced the number of MPs from 0.50 per liter of wastewater to zero [76]. It should be noted that the highest efficiency of reverse osmosis (RO) in removing MPs occurs with membrane bioreactor technologies (MBRs). Membrane bioreactor technology is a system that includes physical methods, activated sludge, and membrane filtration [74]. Since the final effluent from sewage treatment is one of the entranceways of MPs to water resources, it is necessary to use an appropriate method to treat and remove this pollutant before discharge. According to a study conducted by Talvitie et al. in 2017, the removal rate of MPs by membrane bioreactor was measured at 99.4%, which shows the high efficiency of this technology compared to other methods so far [77]. Despite the high costs of membrane filters and MBRs, they are more effective in removing MPs when combined with other treatment processes [74]. Lee et al. investigated a new method for removing MPs from water that overcomes the limitations of traditional membrane filtration, such as membrane clogging and fouling. This innovative approach combines electrokinetic with physical filtration and significantly increases the removal rate of small plastic particles. It is noteworthy that the electrokinetic process, which relies on particle mobility, ensures robust performance regardless of the type, size, concentration, or chemical composition of MPs. This system achieves more than 99.9% removal efficiency and a filtration rate of about 10,000 L m (2) h (-1). The results of this study highlight the potential of the electrokinetic system as an effective solution to deal with microplastic pollution in aquatic environments [78].

According to a study of Moses et al., the use of biochar modified with iron (FeBC) and Fe/Zn in water removed 96.24 and 84.77% of polystyrene (PS-MPs) at a dose of 3 g/L in water, respectively. The removal efficiency decreased in alkaline conditions and with weak acidic ions. The FeBC removed 72.39% and 78.33% of PS-MPs from drinking water and lakes at an initial concentration of 20 mg/L, respectively, although it was ineffective in biogas slurry and beer wastewater due to competitive adsorption [79].

Biomaterials that are extracted from biological sources can be prioritized in water treatment for the removal and separation of MPs due to their compatibility with the environment and their renewable nature. One of the advantages of this method is selectivity, which is used with the help of surface modification and chemical engineering to remove different types of MPs with different origins, compositions, and sizes [80, 81]. Due to their biodegradability and natural origin, these materials have lower energy consumption and operating costs than traditional chemical and physical methods. However, factors such as dose and type of coagulant, coagulation time, characteristics of MPs, and water quality influence biomaterials effectiveness [82]. One of the materials used is fibrous cellulose which works through filtration. Studies have demonstrated the effective use of various biochars from biological sources, including lignin [83], wood and corn straw [84], and jujube [85], as filters to remove MPs, with an efficiency ranging from 93 to 99%. These biochars have been improved using chemical and physical processes to have higher efficiency in absorbing MPs. For example, biochars modified with polyethylene amine [86] polyethylene glycol and magnetic nanoparticles have shown a high ability to remove MPs from water [84, 87, 88]. In addition, vegetable protein sponges [89], chitin-graphene oxide sponges [90], chitin-carbon black sponges [91], chitosan nanofibers, and biochars such as rice husk modified with magnetic particles [87] are known as adsorbents with high capacity to absorb and destroy MPs in water. Due to their light and porous structure, these materials have a good performance in removing MPs from water [92]. Innovation in nanotechnology and functionalization of biomaterials can help in their selectivity, efficiency, and stability [83, 85]. On the other hand, the process of coagulation, flocculation, and finally sedimentation of particles is an important method for removing MPs [82]. Among the most widely used coagulants are aluminum and iron salts, whose positive charge has the ability to neutralize the negative charge of MPS and their precipitation [93]. The low efficiency of these coagulants has been improved by combining them with organic coagulants such as pectin [94]. Extracellular polymers such as bacterial cellulose also can flocculate MPS. In addition to high biodegradability, these materials produce less sludge [95, 96]. In one of the methods to remove MPs, the combination of traditional polyaluminium chloride (PAC) coagulants with modified starch were used. This method not only reduced the need for PAC but also utilized three mechanisms: absorption bridge mechanisms, electrical neutralization, and sweep mechanisms. Ultimately, 97% of MPs were absorbed with the help of filtration in the coagulation effluent, while the use of biochar achieved a removal efficiency of 90% [97].

4. Conclusion

This narrative review underscores the alarming growth of microplastic (MP) pollution in aquatic environments, emphasizing their diverse origins, pervasive presence, and severe ecological impacts. Microplastics are introduced through both primary and secondary sources, such as industrial products and the degradation of larger plastic debris, and traverse various pathways, including runoff, sewage discharge, and atmospheric deposition. These pollutants threaten aquatic ecosystems by causing oxidative stress, metabolic disorders, and other physiological disruptions in organisms, while also acting as carriers for hazardous pollutants such as heavy metals. To mitigate MP pollution, different methods and technologies have different efficiency and disadvantages in removing all kinds of MPs. However, it is recommended that this combination of different aspects of technology be investigated in reducing and eliminating all types of MPs, improving efficiency and effect on the environment. A comprehensive approach that combines technological innovations, preventive measures, and collaborative efforts is essential to address this environmental challenge and protect aquatic ecosystems.

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Ethical Approval

Also, Ethics License of the present study was acquired from the Ethics Committee of Ahvaz Jundishapur University of Medical Sciences (Code of ethics: IR.AJUMS.REC.1401.140).

Authors' Contribution

HA-E, FK, MJ-M, ST, MH, and MT were principal investigators of the study and drafted the manuscript. NS, MF, and MJ-M were advisors of the study. HA-E, FK, MJ-M, ST, MH, and MT performed the statistical analysis. All authors contributed to the design and data analysis and assisted in the preparation of the final version of the manuscript. All authors read and approved the final version of the manuscript.

Competing Interests

No conflict of interest was declared by the authors.

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