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MICROPLASTICS IN THE ENVIRONMENT: PROPERTIES, IMPACTS AND REMOVAL STRATEGIES

(Mikroplastik dalam Alam Sekitar: Sifat, Kesan dan Strategi Penyingkiran)

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Abstract

Microplastics (MPs) constitute an emerging class of pollutants that have garnered significant attention due to their omnipresence in marine and freshwater ecosystems. Particles with a diameter of less than 5 mm result from the degradation of larger plastic debris and the production of commercial plastic products. The pervasive occurrence of MPs in the environment is a primary concern due to their potential adverse effects on marine organisms and human health. MPs' high specific surface area and hydrophobicity make them effective adsorbents of other pollutants. Consequently, ingestion of MPs by organisms can lead to enhanced toxicity and bioaccumulation of these pollutants, causing significant harm to the ecosystem. This study offers a comprehensive overview of the properties of MPs, the routes of their entry into the environment, their impacts on environmental and human health, and current approaches for their removal. Physical, chemical, and biological methods for MP removal are discussed, including their benefits and drawbacks. However, there is an urgent need to develop novel, efficient, and cost-effective techniques for MP removal. The insights presented in this review aim to guide policymakers, scientists, and stakeholders in promoting sustainable management practices.

Keywords: microplastics, chemical contaminants, wastewater treatment plants, removal techniques

Abstrak

Mikroplastik (MP) merupakan kelas pencemar yang muncul dan telah mendapat perhatian utama pada masa ini kerana kehadirannya di dalam ekosistem marin dan air tawar. Zarah-zarah dengan diameter kurang daripada 5 mm ini terhasil daripada degradasi serpihan plastik yang lebih besar dan pengeluaran produk plastik komersial. Kemunculan MP yang berleluasa di alam sekitar ini telah menimbulkan kebimbangan kerana ianya berpotensi memberi kesan buruk terhadap organisma marin dan kesihatan manusia. Luas permukaan spesifik yang tinggi dan hidrofobik MP menjadikannya sebagai penjerap yang berkesan bagi bahan pencemar lain. Oleh itu, pendedahan MP terhadap organisma boleh membawa kepada peningkatan ketoksikan dan bioakumulasi bahan pencemar ini, dan seterusnya menyebabkan kemudaratan yang ketara kepada ekosistem. Ulasan ini memberikan gambaran menyeluruh tentang sifat-sifat MP, laluan masuk ke alam sekitar, kesannya terhadap alam sekitar dan kesihatan manusia, dan pendekatan semasa untuk penyingkiran mereka. Kaedah fizikal, kimia dan biologi untuk penyingkiran MP dibincangkan, termasuk kelebihan dan kelemahannya. Walau bagaimanapun, terdapat keperluan mendesak untuk membangunkan teknik baru yang cekap dan kos yang efektif untuk penyingkiran MP. Ulasan ini memberikan pandangan yang berharga untuk penggubal dasar, saintis dan pihak berkepentingan untuk menggalakkan amalan pengurusan yang mampan dan mengurangkan percambahan MP dalam alam sekitar.

Kata kunci: mikroplastik, pencemar kimia, loji rawatan sisa air, teknik penyingkiran

Introduction

Global plastic production has grown rapidly in the past few decades. According to the United Nations, plastic production reached 359 million metric tons in 2018, a significant increase from 1.5 million metric tons in 1950 [1]. This substantial growth, amounting to over 200 times in just 68 years, can be attributed to several factors, such as population growth, urbanization, and the ascendancy of the global consumer culture. However, if the current rate of plastic production persists, experts predict that plastic waste production will triple by 2050 [2].

The increase in plastic production has led to a global surge in plastic waste generation, becoming a significant environmental concern due to the inadequate management of plastic waste. As a result, plastic debris has accumulated in various environmental matrices, such as marine and terrestrial environments. Plastic waste can persist for decades in the environment, with several harmful impacts on the environment and biota. In marine environments, the accumulation of plastic debris has been found to cause entanglement and ingestion by marine animals, leading to physical injuries, suffocation, and mortality [3]. The ingestion of plastic debris can also negatively impact the health of these organisms, such as reduced feeding efficiency, malnutrition, and reproductive impairment [4]. Additionally, plastic debris can act as a carrier for invasive species and pathogens, resulting in ecological disruptions and the spread of diseases [5,6]. In terrestrial environments, plastic debris can lead to soil and water pollution, which, in turn, can have harmful effects on soil quality, crop productivity, and human health [7, 8].

Plastic debris undergoes a process of degradation, leading to the formation of microplastics (MPs), which are defined as plastic particles smaller than 5 mm [9, 10]. MPs can be classified into two categories based on their origin: primary and secondary (Figure 1a). Primary MPs are deliberately manufactured and added to products, such as microbeads in personal care items or plastic pellets used in production processes [11, 12]. Secondary MPs are produced by the fragmentation, degradation, and weathering of larger plastic debris through natural and anthropogenic processes [13-15]. These small plastic particles enter the aquatic, terrestrial, and air environments through several activities on land and in the marine environment (Figure 1b). Table 1 summarizes the potential roots of primary and secondary MPs in the environment. Additionally, MPs are categorized according to their physical properties, including shape, size, and chemical composition. They can have either spherical or irregular shapes. They may contain various additives, such as plasticizers, stabilizers, and flame retardants, which can leach into the environment, posing potential risks to human health and ecosystems, as presented in Figure 1c [16].

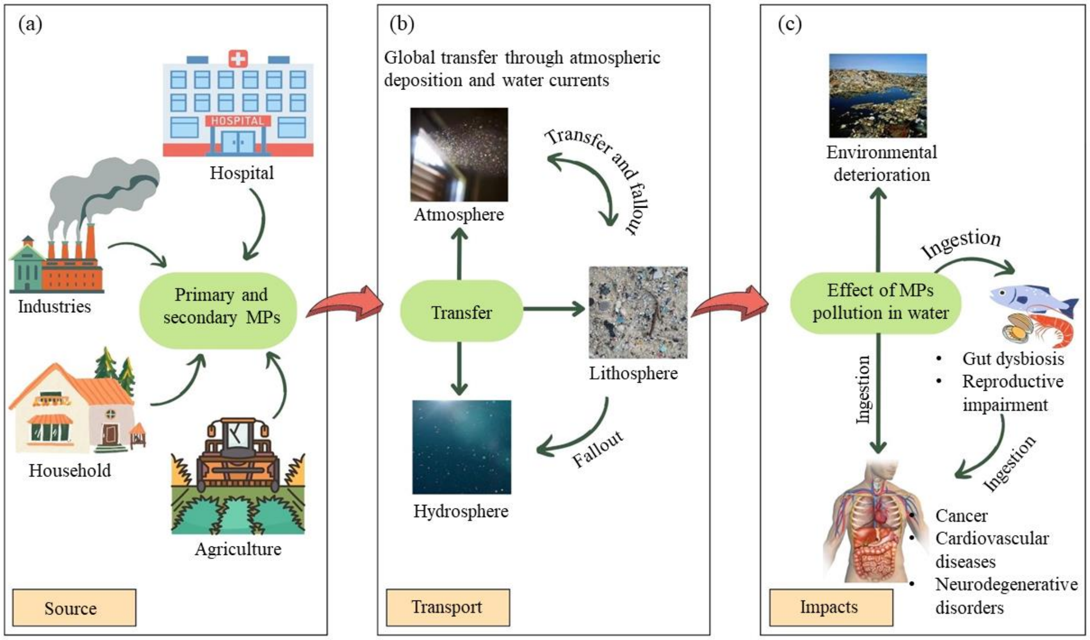

Figure 1. The schematic diagram of (a) the main sources of MPs, (b) transportation of MPs into the environment, and (c) environmental impacts and health effects on living organisms

Table 1. Summary of the potential roots of primary and secondary MPs in the environment

Primary MPs	Secondary MPs
Microfibres detached from synthetic textiles [17]	Degradation of larger plastics [18, 19]
Microbeads usually used in personal care, such as face scrub, body wash, toothpaste, etc. [12, 20]	Poor management of single-use plastics such as PPE [21]
Resin particles are used as industrial feedstock [22]	Aged and broken plastic debris due to environmental pressure [23, 24]
Medical applications such as dentistry products [25]	Tiny particles from the weathering of agricultural plastic film [22]
Dust from abrasions on car tires [26]	Plastic mulch film (PE) is used to improve water use efficiency and crop yield [8]
Ingredients that have been used for plastics production [2]	Plastic release during the mechanical recycling process [25]

The presence of MPs in the environment is a growing concern, and their detection has become increasingly common in various environmental compartments such as water, sediment, and soil. Among the different types of MPs, polyethylene (PE) and polypropylene (PP) are frequently detected in environmental samples, and their abundance is linked to their widespread use in products such as plastic bags, food packaging, and bottles [8, 24, 27]. Similarly, polystyrene (PS), commonly used in disposable food containers, cups, and packaging materials, is also frequently found in environmental samples, including freshwater and marine systems. Nylon (PA), utilized in textiles, fishing nets, and ropes, is another type of microplastic commonly detected in environmental samples, including water, sediment, and biota [28]. Polyethylene terephthalate (PET), used in water bottles, food packaging, and textiles, has also been found in various environmental compartments [25, 29, 30]. PET is known to resist environmental degradation, and studies have estimated its half-life to be hundreds of years under certain conditions. Table 2 summarizes the types of MPs, their applications, and estimated degradation time in the environment.

Table 2. Summary of the types, applications, and estimated degradation time of MPs

Type of Polymers	Chemical Formula	Application	Estimated Degradation Time	References
Polyvinyl chloride (PVC)	$(C_2H_3Cl)_n$	Building and construction sector	Up to 100 years	[28, 31]
Polyamide (PA) or nylon	$(C_{12}H_{22}N_2O_2)_n$	Gears, bushings, bearings, stockings, fabric, carpets, fishing line, and cable coatings	20 – 200 years	[31]
Polyethylene (PE)	$(C_2H_4)_n$	Shopping bags, cosmetic products, bottles, food packaging	Up to 1000 years	[28, 31]
Polypropylene (PP)	$(C_3H_6)_n$	Medicine bottles, bank notes, hinged caps	20-30 years	[28, 31]
Polystyrene (PS)	$(C_8H_8)_n$	Building insulation, inner line of fridge, food packaging	Up to 500 years	[28, 31]
Polyethylene terephthalate (PET)	$(C_{10}H_8O_4)_n$	Personal care products, water bottles, food packaging films	Up to 450 years	[28, 32]

Physicochemical properties of microplastic

The diverse range of MPs in the environment can be classified based on their distinctive shapes, including fibers, fragments, pellets, films, microbeads, and foams. These various shapes can result from the different types of transformations that MPs undergo, which can alter their physicochemical properties [33]. Among the various transformation processes, a previous study reported that chemical degradation induced by UV radiation is the most critical, initiating the initial degradation processes of microplastic particles [34]. The degradation of MPs can result in the formation of smaller particles, which can further contribute to the accumulation of MPs in the environment and increase the risk of exposure to humans and wildlife.

Polymers also possess unique physicochemical properties, including crystallinity, density, surface charge, surface area, surface hydrophobicity, and additives, influenced by their chemical compositions [23, 35]. The crystallinity of a polymer is a crucial characteristic that can affect the density of MPs. For instance, semi-crystalline polymers like PE and PP have low densities and tend to float in water [13, 16]. However, the crystallinity of a polymer can be altered by various environmental pressures, which can have significant implications for its other physicochemical properties [36]. Other physicochemical properties of MPs include surface charge, surface area, surface hydrophobicity, and the presence of additives, which can impact their stability, reactivity, and fate in the environment [37].

On the other hand, polymers with highly aromatic structures, such as PS, have unique physicochemical properties that make them highly adsorbent and susceptible to environmental pressures [38, 39]. In the case of PS, the strong π-electron-rich aromatic rings within the polymer structure trigger its sorption capacity and enable it to selectively adsorb certain pollutants, including aromatic organic pollutants [40]. However, environmental factors such as temperature, pH, and salinity can alter the π-electron density of the polymer, leading to changes in the sorption capacity and selectivity of the material [35]. Therefore, understanding the physicochemical properties of MPs is crucial in evaluating their fate and transport in the environment and their potential impacts on ecosystems and human health [23, 35].

Routes of entry to the environment

MPs have been identified as a pervasive and persistent form of pollution across the hydrosphere, lithosphere, and atmosphere worldwide. Figure 2 presents a schematic diagram illustrating the transportation of MPs into the environment. According to a global review by Fadare et al., MPs have been detected in various aquatic environments, including oceans, rivers, lakes, and estuaries, as well as in terrestrial environments such as soil and air [41]. A study by Zhang et al. found that MP concentrations in soils from urban areas in China ranged from 8 to 1730 particles/kg, with higher concentrations near plastic waste recycling facilities [42]. In a study on sediments from the Mekong River Delta in Vietnam, Kieu-Le et al. discovered MPs in all samples collected, with a mean concentration of 6.0 ± 2.0 particles per/g of dry sediment [43].

Similarly, microplastic concentrations ranging from 9.73 to 89.16 particles/m^{-3} were found in nine estuaries in Jakarta Bay, Indonesia [44]. MPs can be transported over long distances and accumulate in various aquatic organisms in aquatic environments, posing potential ecological and health risks. A study by Lahive et al. found widespread MP contamination in Asian freshwater ecosystems, with high concentrations detected in sediments and benthic organisms such as snails and worms. The study also revealed that MPs transferred up the food chain to fish and other aquatic organisms, potentially exposing humans through consumption [45].

Wastewater treatment plants (WWTPs) have been identified as significant contributors to MP release into the environment, releasing approximately 1,500 trillion microplastic particles annually [46]. MPs enter WWTPs through the direct discharge of microplastic-containing wastewater from domestic and industrial sources and the shedding of MPs from synthetic textiles during washing. Several studies have reported the abundance of MPs in WWTPs, highlighting their significant contribution to the overall pollution of the aquatic environment. For instance, Li et al. found that the concentration of MPs in WWTP influent ranged from 1.5 to 21.3 particles/L, with an average of 7.5 particles/L. The study also noted an increase in MP concentration in the effluent, with an average of 22.2 particles/L [47]. Mason et al. conducted a study in 17 wastewater treatment facilities in the United States, revealing an average of 0.05 MP/L in the final effluent, equating to a daily discharge into the environment of more than 4 million MPs, with microfibers identified as a dominant type of MPs in the influent and effluent of WWTPs. Regarding MP size, they also found that 57% had a size between 0.125 mm and 0.355 mm, while 43% of MPs were larger than 0.355 mm [48]. Another study by Deng et al. analyzed the influent and effluent of WWTPs in Shaoxing City, China, and found that the mean concentration of MPs in the influent was 334 particles/L, with a range of 1 to 16 particles/L from a textile dyeing WWTPs [49].

The shape and types of MPs found in WWTPs vary depending on their sources and treatment processes. For example, a study by Alvim et al. identified microbeads and fragments of larger plastic debris as the dominant types of MPs in WWTP effluent, while microfibers were more prevalent in the influent [50]. The study also found that the MPs' shape was mainly irregular, with sizes ranging from 1 to 5 mm. Another study by Viitala et al. found that fibers were the dominant shape of MPs in WWTP effluent, accounting for 77% of the total MPs, followed by fragments. Most MPs were smaller than 1 mm, with sizes ranging from 100–500 µm [51].

In the atmosphere, MPs can be transported over long distances and have been detected in remote areas such as the Arctic and Antarctic. The main sources of MPs in the atmosphere are synthetic fabrics, tire deterioration from synthetic rubber, and urban dust [52]. A study by Klein & Fischer in urban areas in Hamburg, Germany, found 2652 MPs particles in atmospheric fallout samples, with a median abundance of 275 MPs/m^2/day [53]. Sridharan et al. found that the MPs and micro rubber (MR) particles predominated in street dust samples retrieved from 15 sites in Asaluyeh, southern Iran, with average concentrations as high as 900 MPs and 250 MRs per 15g of the sample, respectively [54]. In another study by Kacprzak & Tijing, the findings demonstrate that the concentration of microfibers in the indoor environment, ranging from 1 to 60 particles/m^3, was higher compared to outdoors, with a range of 0.3 to 1.5 particles/m^3. The sizes ranged from 50 to 3250 µm indoors and 50 to 1650 µm outdoors [34]. The study also found that the concentration of microfibers in the indoor environment was higher, possibly due to friction, heating, lighting, or wear and tear of various plastic items. A previous study by Sangkhram et al. reported that airborne MPs were mostly PE, PS, PET, and other fibers, with sizes ranging from 10 to 8000 µm [55].

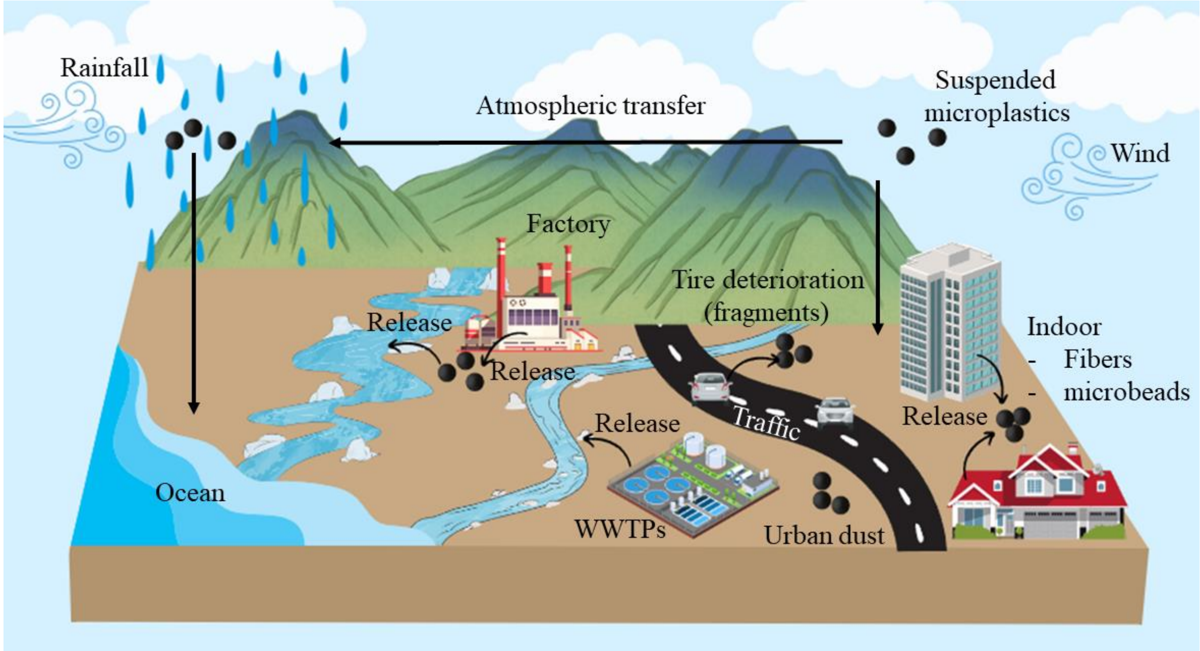

Figure 2. Schematic diagram of the transportation of MPs into the environment

Microplastics as vectors for chemical contaminants

MPs pose a significant and widespread environmental challenge. Due to their relatively high specific surface areas and hydrophobicity nature, MPs are highly effective at adsorbing various contaminants [56]. MPs are composed of various additives, such as plasticizers, fillers, and stabilizers, which complicate their composition. Moreover, when released into the environment, MPs provide surface area for the adsorption of numerous compounds from the surrounding environment. Examples of chemical pollutants that can adhere to plastics include polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), polybrominated diphenyl ethers (PBDEs), and persistent bioaccumulative and toxic substances (PBTs) [57]. When MPs absorb contaminants from the environment, their toxicity rises, potentially causing harmful effects on human health and aquatic organisms [58] [59]. The sorption of the chemical contaminants on the surface of MPs is influenced by various factors, including the type of polymers, the nature of chemical contaminants, and the environmental conditions [60]. In this section, we explain the factors that influence the sorption behavior and mechanisms of chemical contaminants on the surface of MPs.

The functional groups of the polymers play a crucial role in the adsorption [61]. The formation of pores and oxygen-containing functional groups (including –OH, –COOH, and C–O) may increase the polarity of MP surfaces, enhancing the impact of hydrogen bonding on adsorption and decreasing their ability to adsorb weak polar organic contaminants [62, 63]. Liu et al. highlighted that their polymer types and features can influence the adsorption ability of MPs toward heavy metals. Different polymer types of MPs, including PE, PP, PS, and PVC, exhibit variations in their chemical compositions and surface properties, affecting their adsorption capacity for heavy metals. For instance, similar to the adsorption of aromatic pollutants, MPs with a higher density of oxygen-containing functional groups, such as carboxyl, hydroxyl, and amino groups, tend to exhibit enhanced adsorption capacities due to the availability of more binding sites for metal ions [64]. For example, PS, a common type of microplastic, has an aromatic compound that triggers its sorption capacity. PS tends to sorb organic aromatic pollutants at different polarities due to π-π electron interaction, making it an effective carrier of these contaminants [40]. Recent research has also demonstrated that MPs can carry hydrophilic pollutants in aqueous environments. Anastopoulos et al. have shown that PE, PVC, and polynorbornene (PN6) can transport azo dye, a model textile wastewater contaminant. PN6 demonstrated the highest sorption capability, followed by PE and PVC, due to electronegative N and O atoms in the PN6 polymeric structure, which can easily form hydrogen bonds with electropositive azo dye atoms [65]. Furthermore, biofilm formation on the surface of the MPs may affect the physical and chemical characteristics, including morphological surface and hydrophobicity, impacting the transportation, sinking, weathering, and fragmentation of MPs in the environment [66]. Cui et al. also report that the sorption of PBDEs, PCBs, α-hexabromocyclododecane (HBCDD), and organophosphate flame retardants (OPFRs) is influenced by the presence of biofilm on the surface of high-density polyethylene (HDPE) compared to virgin HDPE [36].

In the literature, it is established that the functional groups and ionic properties of chemical contaminants influence their polarity [61]. Different polymers may exhibit varying sorption capacities for hydrophobic organic contaminants [67]. The log K_{ow} is commonly used to describe the polarity of the contaminants, where organic contaminants with a higher log K_{ow} are classified as hydrophobic and are more prone to adsorption on the surface of MPs [68]. For example, a study conducted by Li et al. demonstrated that hydrophobic antibiotics with higher log K_{ow} values were more attracted to PP, PS, PE, and PVC [69]. On the other hand, the sorption behaviors of organic contaminants on the surface of MPs are significantly influenced by the molecular structure of organic pollutants. For instance, sulfanilamide antibiotics, composed of bonded carbon and hydrogen atoms, readily adhere to and bind on the surface of MPs in the environment [70].

In addition to the properties of MPs, environmental variables such as pH and salinity significantly influence the adsorption of heavy metals onto MPs. Liu et al. emphasized that the pH of the solution affects both the surface charge of MPs and the speciation of metal ions, thereby influencing their electrostatic interactions and complexation processes. Generally, MPs exhibit higher adsorption capacities for heavy metals under acidic conditions (lower pH) due to increased positive surface charge and higher concentrations of metal ions. On the other hand, the salinity of the environment can also impact heavy metal adsorption by MPs. Elevated salinity levels increase the ionic strength of the solution, leading to competition between metal ions and salt ions for adsorption sites on MPs. As a result, the adsorption of heavy metals by MPs may decrease under high salinity conditions [64]. Furthermore, the size and shape of MPs play a crucial role, with smaller MPs possessing larger surface areas and, consequently, higher adsorption capacities. Irregularly shaped MPs with rough surfaces also provide more active sites for metal binding than their spherical counterparts.

Effects of microplastics pollution in water

The presence of MPs in aquatic environments has been extensively documented in numerous studies. In a recent investigation conducted by Hu et al. [16], the influence of environmental variables on the adsorption of heavy metals onto MPs was explored. Additionally, Liu et al. emphasized that the pH of the solution affects both the surface charge of MPs and the speciation of metal ions, thereby influencing their electrostatic interactions and complexation processes. Generally, MPs exhibit higher adsorption capacities for heavy metals under acidic conditions (lower pH) due to an increased positive surface charge and higher concentrations of metal ions. On the other hand, the salinity of the environment can also impact heavy metal adsorption by MPs. Elevated salinity levels increase the ionic strength of the solution, leading to competition between metal ions and salt ions for adsorption sites on MPs. As a result, the adsorption of heavy metals by MPs may decrease under high salinity conditions [16]. This distribution of polymer types and shapes also highlights MPs' widespread contamination of freshwater ecosystems. The small size of MPs enables their easy entry into aquatic environments, where they can persist for extended periods and potentially pose significant risks to the ecosystem and human health. This section will concisely elaborate on the effects of MP pollution in water.

Effects of microplastics on the aquatic environment

MPs pose a growing concern in marine ecosystems due to their small size, making them easily mistaken for food by various marine species. The ingestion of MPs by marine organisms, such as zooplankton [71], bivalves [72] [73, 74], fishes [75], and shrimps [76], can lead to detrimental effects on their physiological functions. MPs with sharp edges can cause mechanical injuries in the digestive tract, leading to inflammation and other complications. Additionally, MPs can act as carriers of harmful chemicals, including heavy metals, organic pollutants, and plasticizers. These chemicals have the potential to pass through the gut wall and enter the circulatory system of marine organisms, leading to disruptions in reproductive and nutritional systems, as well as inducing inflammation in essential organs [4]. The vulnerability of marine organisms to the detrimental effects of MPs extends to critical stages of their life cycles. Zhang et al. highlighted the high susceptibility of sea turtle eggs to the permeation of pollutants from microplastics. MPs near sea turtle nesting areas pose a significant threat to embryonic development, diminishing hatching success and ultimately jeopardizing population sustainability. The chemicals present in MPs can interfere with embryonic development, disrupt hormonal balance, and compromise sea turtle embryos' overall health and survival [77].

Effects of microplastics on humans

The ingestion of MPs is recognized as the primary route of human exposure to these particles. Recent research has shed light on the extent of this exposure pathway and its potential implications for human health. Research indicates that the average person consumes approximately 39,000 to 52,000 synthetic plastic debris particles annually, with age and gender also having an effect [42]. Furthermore, MPs have been detected in various food items, including seafood, table salt, honey, and beverage packaging, suggesting that dietary intake is a significant contributor to human exposure [41, 78-82]. Once ingested, MPs can translocate from the gastrointestinal tract to various organs and tissues within the body. Turroni et al. emphasized that MPs can enter organs such as the liver, kidneys, and gastrointestinal tract, potentially leading to health effects [83]. The physical presence of MPs in these organs can induce mechanical damage, leading to tissue inflammation and impairing normal physiological functions [84]. Additionally, chronic exposure to MPs has been associated with impaired nutrient absorption in the gastrointestinal tract, disrupting metabolic processes and overall health [85].

Bhatt et al. [4], Golwala et al. [86], and Rahman et al. [87] highlighted the potential harm caused by the release of pollutants, including endocrine disruptors, heavy metals, and persistent organic pollutants from MPs. These pollutants accumulate in various tissues and organs, posing significant risks to human health. Chronic exposure to MPs carrying these pollutants can lead to adverse effects on tissues and systems in the body, including inflammation, oxidative stress, and disruption of hormonal balance. MPs can potentially cause physical harm to organs by blocking the digestive tract, harming intestinal tissues, and affecting cells' filtering and phagocytic activity [88]. Moreover, in vitro studies have demonstrated that exposure to MPs and nano-plastics can trigger cytotoxic effects on cerebral and epithelial human cells through the generation of oxidative stress [89]. This type of stress arises from an imbalance between reactive oxygen species (ROS) production and the cellular ability to detoxify them, leading to the oxidation of vital cellular components such as lipids, proteins, and DNA [90]. The resulting damage can lead to various adverse health outcomes, including cell death, inflammation, and the development of chronic diseases like cancer, cardiovascular disease, and neurodegenerative disorders [91].

Microplastics removal approaches

Removing MPs in WWTPs involves implementing different physical, chemical, and biological techniques. These methods aim to effectively reduce the concentration of MPs in wastewater before its discharge into the environment. In Table 3, a summary of the existing removal techniques in WWTPs can be found, illustrating the range of approaches employed for this purpose.

Physical techniques

Filtration is a widely recognized and effective method for removing MPs from various sources. The principle behind filtration involves passing a liquid through a filter medium with pores smaller than the particle size of the target contaminants. Standard filtration tools include a funnel, filter membrane, and vacuum pump [92]. In the case of MPs, the liquid containing MPs is poured into the funnel, and the vacuum pump creates a pressure difference that drives the liquid through the filter membrane [93]. As the liquid containing MPs flows through the ultrafiltration membrane, the smaller pores of the membrane selectively block the passage of the MPs while allowing the liquid to pass through [94]. This process ensures the separation and removal of MPs, contributing to the purification of the liquid. The captured MPs remain on the surface or within the membrane, forming a retained fraction that can be subsequently collected and properly disposed of. Figure 3a clearly illustrates how membrane filtration acts as an effective barrier to the passage of MPs, highlighting its potential as a valuable method for MP removal.

Adsorption has emerged as a promising method for effectively removing MPs from aqueous solutions due to its potential for high efficiency and cost-effectiveness. In a recent study conducted by Tang et al. [59], the use of magnetic carbon nanotubes (M-CNTs) as an adsorbent material for the complete removal of three common types of MPs: polyethylene (PE), polyethylene terephthalate (PET), and polyamide (PA), was investigated. The experimental setup involved mixing 5g/L of each type of MP with 5g/L of M-CNTs and allowing them to adsorb for 300 minutes. The study revealed that the strong hydrophobic nature of the MPs played a crucial role in their adsorption onto the M-CNTs. Specifically, for PE MPs, the hydrophobicity of the particles was identified as the primary driving force behind their adsorption. The hydrophobic nature of the M-CNTs facilitated the attraction and binding of the hydrophobic MPs, leading to their effective removal from the aqueous solution. In the case of PET MPs, the adsorption mechanism involved a combination of hydrophobic interaction and π-π electron conjugation, facilitating their interaction and adsorption. Additionally, the presence of π-π electron conjugation, referring to the interaction between the aromatic rings of the MPs and the M-CNTs, further enhanced the adsorption process. Therefore, the combination of hydrophobic interaction and π-π electron conjugation contributed to the efficient removal of PET microplastics.

Similarly, for PA MPs, the adsorption mechanism was found to be more complex, attributed to multiple factors, including π-π electron interaction, complexation, electrostatic interaction, and hydrogen-bond interaction occurring on the surface of the microplastics. The π-π electron interaction involved the interaction between the aromatic rings of the PA molecules and the M-CNTs, facilitating their adsorption. Complexation, electrostatic interaction, and hydrogen-bond interaction between the functional groups present on the surface of the MPs and the M-CNTs also contributed to the adsorption process [20].

Biochar has gained attention as a potential material for removing MPs, offering a promising alternative in addressing the growing concern of MP pollution. A recent study by Wang et al. demonstrated that biochar could remove more than 95% of MPs, making it a highly efficient solution for mitigating MP contamination. The remarkable MP removal efficiency of biochar can be attributed to several factors. The flaky-shaped particles of biochar possess unique properties that facilitate MP removal. These flaky particles can detach themselves from the main biochar structure, increasing surface area exposure and creating more binding sites for MP adsorption. This characteristic enhances the contact between biochar and microplastics, leading to a higher adsorption capacity and more effective removal. Furthermore, the van der Waals forces in the biochar structure play a significant role in MP removal. These intermolecular forces, arising from fluctuations in electron density, contribute to the attractive forces between the biochar and MPs. As a result, MPs experience reduced immobilization through mechanisms such as “Trapped” and “Entangled” (Fig. 3b), where MPs become trapped within the biochar structure or entangled with the biochar particles [96].

Chemical techniques

Coagulation and flocculation techniques have long been recognized as effective methods for removing MPs in WWTPs. The coagulation process involves the addition of coagulants, typically metal salts such as aluminum sulfate ($Al_2(SO_4)_3$) or ferric chloride ($FeCl_3$), to the wastewater. During coagulation, MPs encounter the Al^{3+} ions present in the coagulant. Figure 3c shows the illustration for the coagulation process for MPs removal. The Al^{3+} ions bind to the surfaces of the MPs through interactions with oxygen-containing functional groups, such as carboxyl, hydroxyl, or carbonyl groups. These functional groups are often present on the surface of MPs, resulting from weathering and degradation processes. The binding of Al^{3+} ions to the MPs forms complex species, such as Al-PET in the case of PET MPs, altering the surface properties of the MPs, leading to increased particle size and improved settling characteristics. Additionally, the complexation between Al^{3+} ions and MPs reduces repulsive forces between individual MP particles, promoting their aggregation and the formation of larger flocs. These larger flocs are more easily separated from the wastewater, resulting in the near-complete removal of MPs, as reported by Lu et al. [97].

The electro-coagulation technique is a recent advancement and an effective method for removing MPs from aqueous environments. The electro-coagulation process is based on the principle of electrolysis, where an electric current is applied to electrodes submerged in the wastewater. The electrodes, typically made of aluminum or iron, dissolve electrolytically, generating metal ions in the surrounding solution. The electro-coagulation process offers several mechanisms for the removal of MPs. For instance, the generated metal ions, such as Al^{3+} and Fe^{3+}, can undergo hydrolysis reactions, forming metal hydroxide species, such as $Al\ (OH)_3$ and $Fe(OH)_3$. These metal hydroxide species can adsorb onto the surface of MPs, promoting the accumulation and subsequent removal of the particles. In addition, the metal hydroxide species can act as coagulants, neutralizing the charge on the MPs and causing their aggregation through charge neutralization mechanisms. Various operational parameters influence the effectiveness of the electro-coagulation process for MP removal. Elkhatib et al. reported a high removal efficiency of 98.5% under specific conditions, including adjusting the initial pH to 4 and applying a current density of 2.88 mA/cm^2 to the reactor. The pH adjustment helps create favorable conditions for generating and precipitation metal hydroxide species, which aids in MP removal. The current density applied to the reactor affects the rate of metal ion generation, which, in turn, influences the coagulation and removal of MPs [98].

Photocatalytic degradation is another promising technology for efficiently removing MPs from aqueous environments. This technique harnesses the power of light to activate a catalyst, leading to the generation of electron-hole pairs that can oxidize MPs. Figure 3d demonstrates the process of photocatalytic degradation of MPs. Among the various photocatalysts investigated, carbon and nitrogen-doped titanium dioxide (TiO_2) have shown exceptional performance in visible light absorption and the separation efficiency of electron-hole pairs, making them highly effective for photocatalytic activity. In a study by Tarazona et al., researchers examined using carbon and nitrogen-doped TiO_2 in conjunction with visible light from an LED lamp to remove MPs. The photocatalytic degradation of MPs was evaluated over 50 hours. The results indicated that the green N-TiO_2 semiconductor exhibited a reduction in the mass of high-density polyethylene (HDPE) MPs within the range of 1-6%. Furthermore, when carbon and nitrogen-doped TiO_2 were employed for a reaction time of 50 hours, the removal efficiency increased significantly to 71.77% [99]. Similarly, Nabi et al. reported a high removal efficiency of more than 95% for PS MPs using TiO_2 nanoparticle films for photocatalytic degradation [100].

Biological techniques

Microalgae have been identified as a promising bio-alternative for various wastewater treatment stages and functionalities due to their potential for removing pollutants from water bodies. While microalgae are already used for water treatment, they have been identified as a potential solution for MP removal due to their ability to interact with and aggregate with MPs, as shown in Figure 3e. Cunha et al. reported on the potential of microalgae for microplastic removal [101]. In a study conducted by Cheng and Wang, *Scenedesmus abundans* was found to effectively remove more than 85% of PS, poly(methyl methacrylate) (PMMA), and polylactide (PLA) microparticles. Hetero-aggregation was identified as the main mechanism of MP removal, wherein microalgae and MPs form aggregates through electrostatic attraction, hydrogen bonding, and van der Waals forces, leading to their separation from the water [102]. Another study by Adegoke also reported that marine seaweed, *Fucus vesiculosus*, was used to determine whether MPs could be removed by translocation in algal tissues. Small canals in the algal cells restricted the flow of MPs, causing the MP particles to become trapped. The study shows that algae removal efficiency was around 94.5% in certain regions [103]. However, MPs' removal efficiency was influenced by several factors, including microalgal density, microplastic concentration, and contact time.

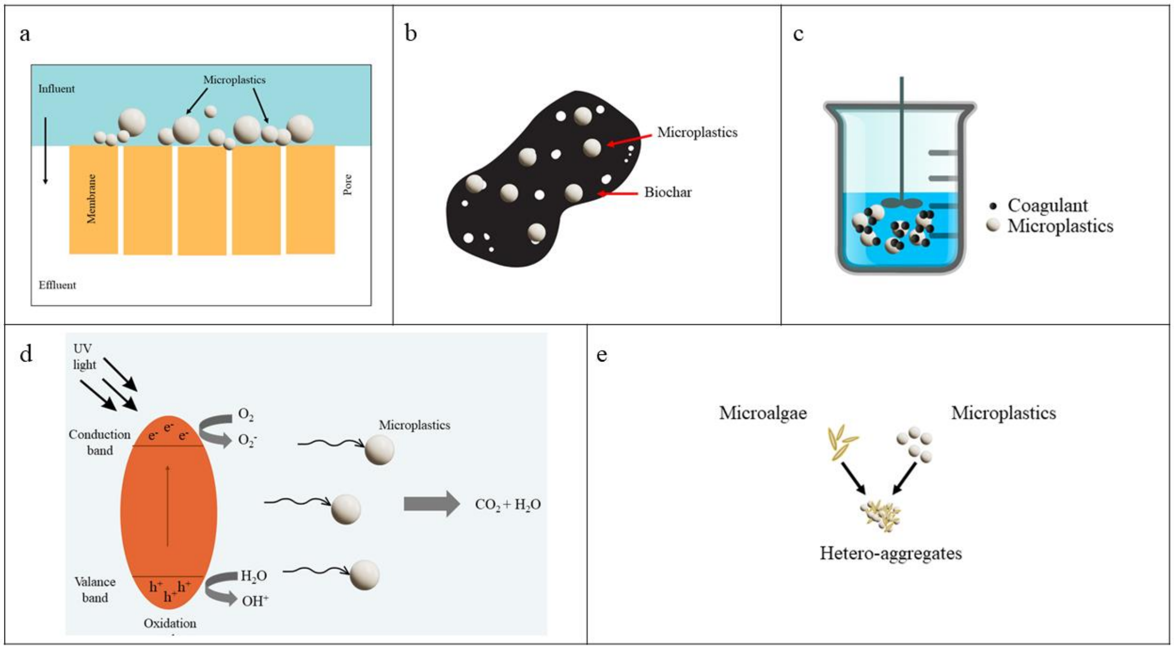

Figure 3. Schematic diagram of main MPs removal approaches (a) membrane filtration, (b) biochar adsorption, (c) coagulation treatment, (d) photocatalytic degradation, and (e) microalgae treatment.

Table 3. Summary of physical, chemical, and biological techniques for MP removal

Removal Techniques Approach	**Type of MPS**	**Mechanisms**	**Efficiency**	**References**
Filtration by biochar	PS microsphere	The van der Waals forces have resulted in less immobilization by the “Trapped” and “Entangled” mechanisms	<95%	[96]
Adsorption by magnetic carbon nanotube	PE, PET, and PA	The strong hydrophobicity of MPs caused M-CNT adsorption by PE, hydrophobic interaction and π-π electron conjugation caused MCNT adsorption by PET, and π-π electron interaction, complexation, electrostatic interaction, and hydrogen-bond interaction on the PA surface all contributed to M-CNT adsorption.	100%	[20]
Coagulation process	PET	The Al was used as a coagulant to form complexes with MPs by exchanging ligands.	Nearly 100%	[97]
Electro-coagulation	MPs from synthetic and real wastewater	Metal ions (Al^{3+}) discharged from the electrode react with the hydroxide coagulant in the water stream to generate sludge blankets for adhering MPs.	98.5%	[98]
Photocatalytic degradation by carbon and nitrogen-doped TiO_2	HDPE	Degradation of primary HDPE MPs can be accelerated and promoted by altering operational parameters such as temperature and pH during photocatalysis.	1-6% for green N-TiO_2, 71.77% for carbon and N-TiO_2	[99]
Photocatalytic degradation by TiO_2 nanoparticles film	PS	Surface hydrophilicity can facilitate the interaction between semiconductors and plastic particles, resulting in charge transfer and separation, leading to MPs' rapid breakdown.	<95%	[100]
Adsorption on microalgae	PS, PMMA, and PLA	Multiple types of MPs were removed by the microalgae *Scenedesmus abundans*, and the main mechanism of MP removal was identified as hetero-aggregation.	<85%	[102]
Adsorption on microalgae	MPs from environment	Marine seaweed, *Fucus vesiculosus*, was used to remove MPs from the environment by translocation in algal tissues.	94.5%	[103]

Limitation of different techniques and green strategies

Microplastic pollution poses a pressing environmental challenge, demanding effective management strategies. We advocate for the future emphasis on green and environmentally friendly approaches. The following outlines some research challenges and goals to reduce MPs in the environment.

Physical methods commonly used for MP removal have proven effective in eliminating high-density MPs. However, they face limitations in dealing with low-density MPs, generating secondary waste, and exhibiting varying efficacy under different environmental factors [104]. Therefore, a comprehensive approach that integrates multiple methods, such as biological treatment and chemical oxidation, becomes necessary. This integration maximizes MP removal efficacy while minimizing environmental impacts. Integrating physical methods with complementary techniques provides a more sustainable solution for microplastic removal in aquatic systems. Moreover, using environmentally friendly and biology-based materials, including starch and biochar, holds promise as adsorbents and coagulators for MP removal due to their biodegradability and environmental friendliness in aquatic environments [105].

Chemical methods, including photocatalytic oxidation and oxidation removal techniques, promise to eliminate MPs from water. However, their large-scale implementation presents challenges due to their high energy consumption, cost implications, and the potential generation of harmful by-products leading to secondary contamination. Thus, a careful evaluation of the practicality and sustainability of chemical approaches is essential to ensure their effective implementation. Additionally, selecting appropriate catalysts, optimizing operating conditions, and integrating suitable treatment technologies can further enhance the effectiveness of these methods. Regarding environmental impact assessment during sample preparation, the software tool AGREEprep may be considered in the future [106].

Biological approaches, particularly biodegradation by microorganisms, have emerged as promising and eco-friendly strategies for MP removal from aquatic systems. However, the practical implementation of this method can be impeded by the slow rate of complete degradation, leading to the release of toxic metabolites and subsequent secondary contamination [56]. Additionally, the efficacy of biological approaches is affected by multiple factors, including the type of MPs, microbial community composition, and environmental conditions like temperature, pH, and nutrient availability. Therefore, optimizing biodegradation methods, microbial communities, environmental conditions, and operational parameters is crucial to enhancing the potential of biological approaches and making them more suitable for large-scale applications.

Conclusion and Future Perspectives

The contamination of the environment with MPs, caused by anthropogenic activities, is a pervasive problem that affects all environmental matrices. MPs possess unique physicochemical properties that enable them to adsorb other pollutants and act as carriers, leading to their accumulation in the food chain and potentially causing adverse effects on human health and aquatic organisms. While biological techniques hold promise for MP remediation, their removal efficiency still lags behind physical and chemical techniques. Therefore, a multifaceted approach integrating various technologies and strategies is urgently needed. A combination of physical, chemical, and biological methods is necessary to achieve optimal removal of MPs from aquatic and terrestrial systems.

However, a careful evaluation of the limitations and potential environmental impacts of each method is crucial, and the integration of complementary methods is necessary for sustainable remediation. Moreover, effective monitoring and assessment techniques must be developed to determine the extent and sources of MP pollution, enabling the implementation of targeted management strategies to reduce and eliminate sources of contamination. Continued research is also required to identify the long-term effects of MPs on aquatic and terrestrial ecosystems and human health. Furthermore, exploring alternative materials and promoting the circular economy presents a viable solution for reducing plastic waste, significantly reducing MP pollution.

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