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REVIEW

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Removal technologies of microplastics in soil and water environments: review on sources, ecotoxicity, and removal technologies

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Abstract

Microplastics (MP) in the environment has attracted extensive attention due to their ubiquitous occurrence and potential toxic effects; but less attention has been given to the removal technologies of MP in different environmental media. This review covers the sources, ecotoxicities, and removal technologies of MP in soil and water environments reported in previous studies to derive the future research directions for MP removal technologies. Previous studies reported various sources contribute to MP present in soil and water environments, indicating that the source control may be a better strategy than contaminated media treatment for management of MP contamination. Similarly, different terrestrial and aquatic organisms have been used to determine the toxic effects of MP with different characteristics. Previous ecotoxicity studies of MP on soil organisms cover only a small number of species compared to that of MP on aquatic organisms. Therefore, further studies are necessary to investigate the ecotoxic effects of MP on a broader range of soil organisms. Also, since the characteristics of MP are diverse, more ecotoxicity studies in both water and soil environments are required. The review provides an overview of various removal technologies for MP in soil and water and identifies gaps in existing studies. Although more studies have been conducted for removal of MP in water than in soil, they remain in their early stages. More studies are needed for removal of MP removal in soil than in water. With MP in water, most studies have been carried out on a lab scale with artificial wastewaters, thus, studies with natural waters in a pilot or field scale are required. Overall, this review highlights the need for further studies on MP removal technologies for real world applications.

Keywords Microplastic, Pollutants, Removal technologies, Microplastic removal, Ecotoxicity

Introduction

Plastics are extensively used in daily life, industry, and agriculture due to their mass production and versatile properties [1]. Global plastic production steadily increased from 370.5 million tons in 2018 to 400.3 million tons in 2022 and is projected to continue growing [2]. However, the plastic recycling rate remains low at 35.5 million tons, with about 76% of total plastic production disposed of as waste—12% through incineration and 79% through landfilling or environmental discharge [3].

Plastics made of various synthetic polymers are discharged into the environment and plastic waste in the terrestrial and aquatic environment contributes significantly to pollution [4, 5]. Microplastics (MP), defined as

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plastic particles < 5 mm in size, are generated through natural degradation processes such as photolysis and weathering of plastic waste [6]. MP can migrate to different environments, including terrestrial, aquatic, and atmospheric environments [7, 8], and their absorption by living organisms poses toxic effects and increases the risk of human ingestion through the food chain [9, 10]. In addition, biodegradation of MP in the environment is generally difficult, requiring an effective alternative to the problem of MP accumulation in the environment [11].

Various aquatic environments, including the ocean, freshwater, and drinking water sources are contaminated with MP [12, 13]. The main source of MP in the environment is terrestrial environment [14], and MP in aquatic environments largely come from land-based activities including sewage and wastewater generated on land [15, 16]. The total amount of MP in terrestrial environment can be 4–23 times higher than the amount of MP in the ocean [17]. The slow degradation of MP and their biological uptake by aquatic organisms can pose risks to human health through the consumption of affected organisms [18, 19]. Recently, research is being actively conducted to develop technologies for MP removal from water including wastewater treatment plants (WWTPs) [20]. However, quantification and mitigation measures of MP in terrestrial environments is relatively underexplored compared to MP in aquatic environments [21].

To date, review articles have focused on specific aspects of MP-related research, such as MP occurrence in the environment, ecotoxicity of MP, and removal technologies, individually, and no review article has yet reviewed these different aspects of MP in aquatic and terrestrial environments together. Therefore, this review focuses on the occurrence of MP, ecotoxicity of MP, and removal technologies of MP in aquatic and terrestrial environments.

Literature review method

From the literature search using the Web of Science and Google Scholar databases with "MP" in combination with "pollutants", "removal", and "ecotoxicity" as keywords, 1,297 relevant documents were retrieved, of which 262 were review articles (as of March 2024). Among 262 review articles, 28 articles focused on MP removal technologies. Of these, 23 articles discussed removal technologies of MP in water, while only 5 articles focused on removal technologies of MP in soil, suggesting more studies on removal technologies of MP in soil are needed. Figure 1 shows the co-occurrence network of the keywords extracted from the obtained literature related to MP removal technologies. As can be seen in Fig. 1, the nodes representing water environments including marine environment, fresh water, surface water, and drinking water are larger than the nodes representing soil environment, suggesting that research on MP has mainly focused on aquatic environments.

Furthermore, the publications on MP removal technologies from the past three years were reviewed in this study. This approach was adopted since research on MP removal over the past three years accounted for 77.31% of all publications and 70.70% of total citations in the last decade. The changes in the number of publications and citations of the studies on MP removal conducted within the last three years are shown in Fig. 2.

Sources of MP in the environment

Sources of MP in soil environment

Microplastics in soil can come from various sources such as agricultural mulching films, fertilizers, sewage irrigation, and atmospheric deposition (Fig. 3). In particular, agricultural mulching films are considered a major source of terrestrial MP pollution, accounting for up to 30% of all potential terrestrial MP sources [14, 22]. MP generated from the used and disposed mulching films can be accumulated in the soil environment, since MP are generated every year when new mulching films are used [23]. Also, the use of fertilizers in agricultural soil is a potential source of MP in soil [24, 25]. When wastewater sludge is applied to soil as a soil amendment, MP contained in the sludge enter the soil environment [26]. Furthermore, irrigation with water containing MP can add MP to soil environment [27, 28]. MP generated by anthropogenic activities are highly likely to enter the atmosphere and, subsequently, enter the soil environment through wind or rain, especially in large urban areas [29]. MP introduced through atmospheric deposition account for 20% of the total MP present in soil [30]. In addition, plastic waste in landfills are another source of MP in soil [27]. Compared to the other sources, the characteristics and contribution of MP from atmospheric deposition and landfill plastic wastes need further studies [31]

Sources of MP in marine water

Approximately 10–20% of MP in the marine environment comes from marine industries, including beach tourism, fishing, and marine vessels [32]. Additionally, human activities such as shipyards, fish farms, and wastewater treatment plants add MP to the ocean environment [33]. However, previous studies have shown that the main sources of MP in the ocean is surface water runoff and plastic wastes that can go through various processes such as mechanical fragmentation, photolysis, and biodegradation and generate MP [34, 35]. Thus, freshwater MP pollution can eventually contribute to marine MP pollution [36]. Atmospheric deposition is also one of the sources of marine MP, but contribution of freshwater MP

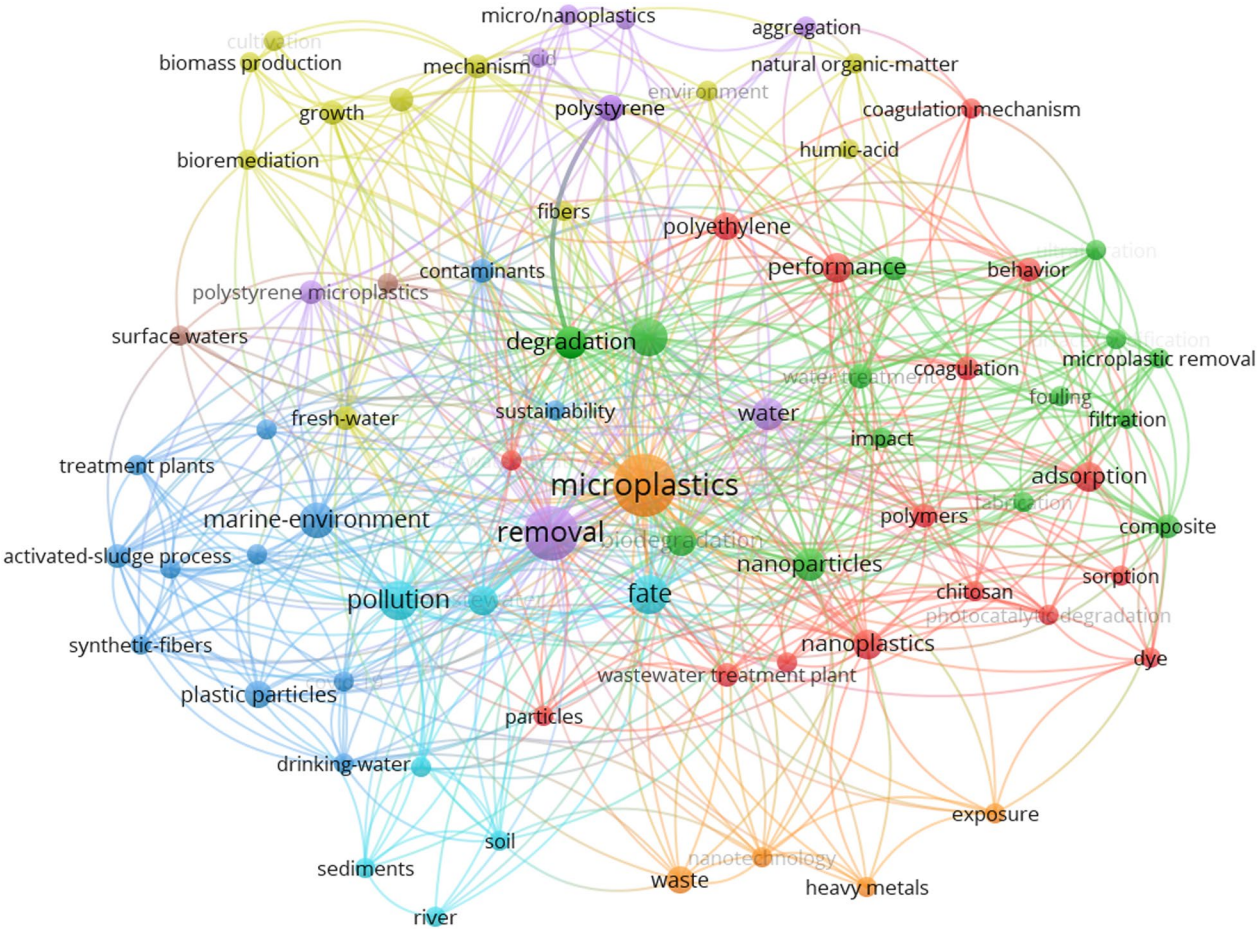


Fig. 1 Co-occurrence network of keywords extracted from the obtained literatures. The size of each node represents the occurrence frequency of the corresponding keyword. The larger the node, the higher the frequency of occurrence

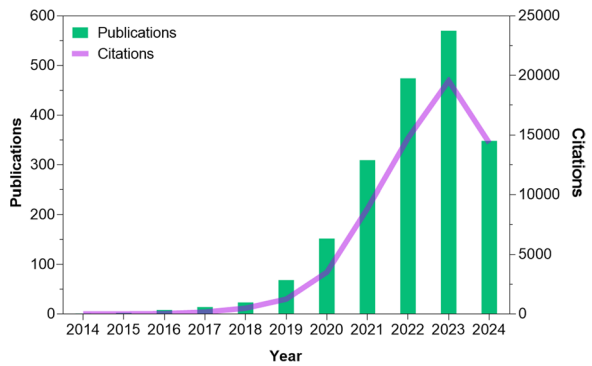


Fig. 2 Citations and publications of microplastic removal studies over time (Generated by 'Web of Science')

is greater than that of atmospheric MP [37]. Stormwater runoff is a potential source of marine MP and moves significant amounts of MP from land to ocean [38].

Sources of MP in freshwater

The presence of MP in freshwater is primarily caused by improper disposal of land-based plastic wastes, leading to its breakdown into smaller particles in the freshwater environments. Sewage discharge is a major source of MP in freshwater [39]. Although wastewater treatment plants treat various domestic sewage and industrial wastewater containing MP, most MP leak into the aquatic environment [40–42]. Therefore, wastewater treatment plants can serve as a temporary storage facility for discharging MP into the environment [43]. Despite the significant MP removal efficiency of wastewater treatment plants, given that wastewater treatment plants are the final step in the artificial water treatment cycle, development of MP treatment technologies and regulations are needed to prevent the entry of MP into the environment [44]. Leachate from landfills can result in MP contamination in nearby rivers, oceans, and soil [45, 46]. Additionally, landfill leachate can reach groundwater contaminating nearby groundwater [47, 48]. Other sources of MP in freshwater include

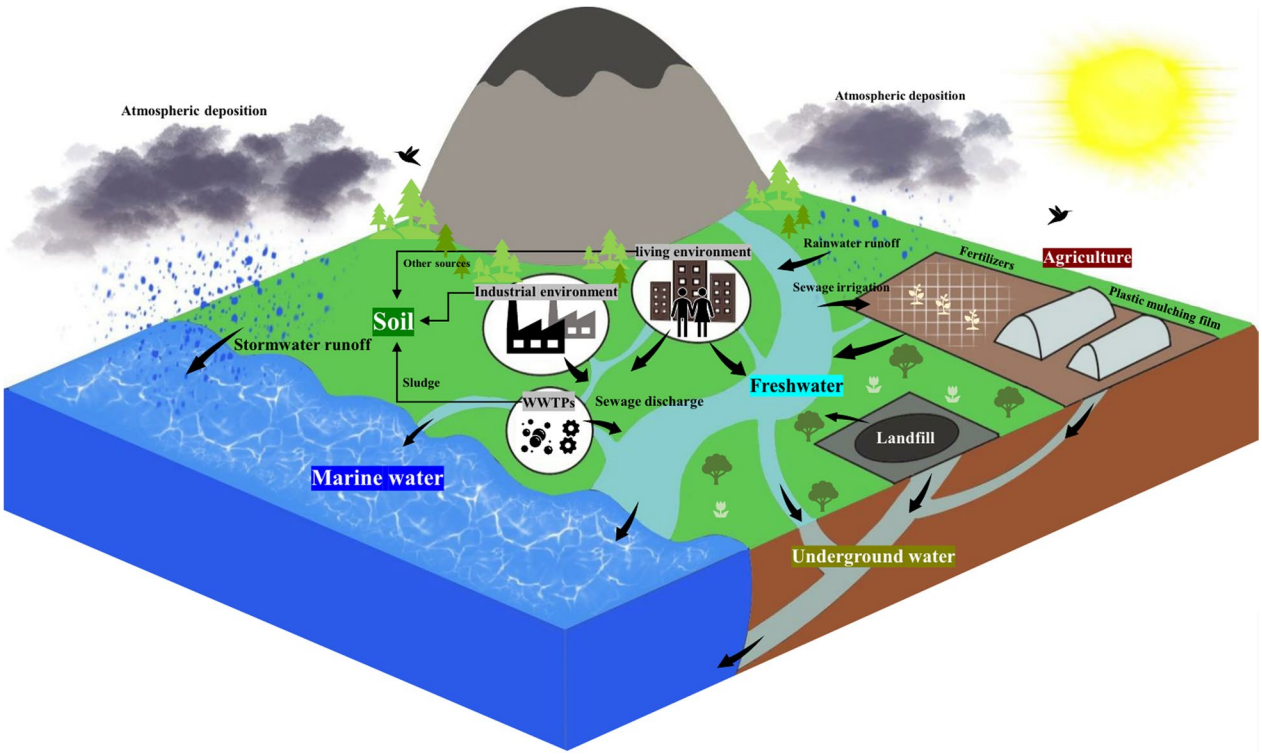


Fig. 3 Sources and transport of microplastics in the environment

mulching plastic films and organic fertilizers used in agricultural soil [14, 49], atmospheric MP [50], and stormwater runoff, especially in cities and highways [38, 51].

Ecotoxicity of MP

Ecotoxicity of MP in soil

MP enter the soil ecosystem through various pathways, such as agricultural plastic mulching films, sludge recycling, and leakage from landfill plastic wastes [52]. Soil contamination with MP causes uptake of MP by soil organisms, which can potentially harm soil organisms [52–54]. Table 1 provides a summary of studies on the toxic effects of MP on soil organisms. Research on the ecotoxicity of MP in soil has been extensively conducted worldwide, with China being one of the actively participating countries (Table 1). Various soil organisms including earthworms, springtails, ants, microorganisms, and plants (e.g., lettuce, chickpea, and tomato) have been used in the toxicity studies of MP in soil (Table 1). The effects of MP on terrestrial plants and earthworms have been reviewed thoroughly in previous studies [67, 68]. These studies indicate that MP did not cause significant lethal effects on soil organisms (Table 1). With earthworms, toxic effects of MP are largely related to the accumulation of the ingested MP [54–57]. For example, exposure 0–3% LDPE MP did not have a significant effect on mortality or growth of earthworms; however, the results indicated that MP ingestion for longer term by earthworms can lead to adverse effects [66]. Since the characteristics of MP (e.g., shape, size, type) are diverse, more studies on the effect of MP on soil organisms need to be carried out considering the diverse characteristics of MP. For example, a previous study reported the effects of MP having different shapes and types on lettuce growth [69]. Recent studies have also reported the effect of coexisting MP and chemicals (e.g., heavy metals, pesticides), which need to be explored further in future studies [52, 70]. Furthermore, the effect of MP on soil microorganisms has been reported in recent review papers [52, 71]. In addition, the ecological toxic effects of MP on soil organisms studied so far have been limited to a few species, requiring more studies on diverse species to enhance the understanding of the effect of MP on soil organisms.

Ecotoxicity of MP in water

Table 2 summarizes recent studies on the ecotoxicity of MP in water environment. Various countries, in particular, European countries have been extensively studying the ecotoxicity of MP in both freshwater and seawater (Table 2). Beyond the direct ecotoxicity of MP themselves, water contamination with MP can lead to problems due to

Table 1 Ecotoxicity of microplastics (MP) in soil

Location	MP type[a] (size)	Organisms (scientific name)	Toxic effects	References
Korea	HDPE fragments (15.94 µm)	Springtail (*Folsomia candida*)	Damage to the digestive tract, Suppressed survival, reproduction, and growth during long-term exposure	[53]
China	PE mulch film (550–1000 µm)	Earthworm (*Metaphire guillelmigut*)	Intestinal microbial reduction and destruction of microbial community networks	[54]
China	PLA, LDPE, and PP particle (10–1000 µm)	Earthworm (*Eisenia fetida*)	Metabolic disorders causing changes in gene regulation, oxidative stress, and signaling inducement, adverse effects on the digestive and immune systems	[55]
India	HDPE particle (40–48 µm)	Earthworm (*Eisenia fetida*)	Oxidative stress due to synergistic interaction between MP and carbendazim	[56]
Serbia	BoPET (75–200 µm)	Earthworm (*Eisenia fetida*)	Suppression of accumulation and proliferation of MP in the intestine	[57]
China	LDPE film (1106 mm)	Ant (*Pheidole* sp., *Paratrechina* sp.)	Active transport of MP by ants in soil environment	[58]
China	PS particle (0.2 µm)	Lettuce (*Lactuca sativa*)	Induction of physiological, transcriptional, and metabolic changes, reduction in biomass and photosynthetic pigments, increase in free oxygen species and antioxidant activity	[59]
China	PS particle (34.4–101.2 nm)	Wheat (*Triticum aestivum L*)	Accumulation of MP in wheat roots, negative effects on growth	[60]
India	PET particle (< 0.45 µm)	Chickpea (*Cicer arietinum*)	Generation of reactive oxygen species inside plant cells, negative effects on germination and growth, damage to plant organelles	[61]
Italy	PET and PVC spherical shape particle (40–50 µm)	Tomato (*Solanum lycopersicum*)	Decrease in fruit quality and nutritionally valuable parameters (e.g., lycopene, total phenols) with PVC MP	[62]
China	PE particle (< 150 µm)	Soil microbial enzyme activity	Inhibition of enzyme activities involved in nitrogen cycle	[63]
China	PS, PE, and PP powders (5–10 µm)	Rhizosphere microbial community	Negative effects on the length and weight of shoots, increased reactive oxygen production rate, reduced peroxidase activity, changes in soluble protein, reduction in soil microbial diversity	[64]
China	PP pellets (200 µm)	Soil nematode community	Negative impacts on soil nematode communities and associated ecological functions	[65]
Korea	LDPE fragments (< 125 µm)	Earthworm (*Eisenia fetida*)	No mortality after 28 d-exposure, skin damage, MP ingestion	[66]

[a] Polyethylene (PE), low density polyethylene (LDPE), high density polyethylene (HDPE), polyethylene terephthalate (PET), biaxially oriented polyethylene terephthalate (BoPET), polylactic acid (PLA), polystyrene (PS), polyvinyl chloride (PVC), polypropylene (PP)

leaching of chemicals such as residual monomers, catalysts, solvents, and additives (e.g., plasticizers, antioxidants, biocides, dyes, etc.) from MP [72]. Small fish and invertebrates can mistakenly uptake MP for food. This can lead to internal accumulation of MP, organ damage by the ingested MP, and increased mortality as shown in Table 2. Furthermore, the ingested MP can be bioconcentrated through the food chain, adversely affecting a wide range of aquatic organisms, including economically important fish species and marine mammals [73]. Filter-feeding organisms like mussels and oysters may ingest MP along with their food, resulting in reduced feeding efficiency, altered energy allocation, and reduced growth and reproduction [74]. The effects of MP on aquatic organisms have been thoroughly reviewed in previous studies [90, 91]. Compared to the ecotoxicity studies on aquatic organisms, ecotoxicity studies on terrestrial organisms are limited [67, 68, 71].

MP removal technologies from soil and water

Removal technologies of MP in soil

Table 3 summarizes recent technologies for the removal of MP from soil. Previous studies used earthworms, microorganisms, and plants to remove MP from soil (Table 3). For example, different sizes (1 and 100 µm)

Table 2 Ecotoxicity of microplastics (MP) in water

Location	MP type[a]	Organisms (scientific name)	Toxic effects	References
Italy	PVC	Sea urchin (*Strongylocentrotus purpuratus*)	Developmental disruption, teratogenicity, high redox stress	[75]
Italy	PP, PS, PE (20 µm)	Octocoral (*Corallium rubrum*)	Mucus release, oxidative DNA damage	[76]
Italy	PE, PVC, ABS	Sea turtles (*Caretta caretta*)	Toxic effects on embryonic tissues	[77]
Italy	PVDF, PLA	Zooplankton (*Artemia ranciscana, Aurelia* sp.)	no effects on survival rate, decrease in pulsation frequency	[78]
China	PS microspheres (70 nm, 500 nm, and 2 µm)	Marine rotifers (*Brachionus plicatilis*)	Intestinal damage and microbial imbalance	[79]
Portugal	Proprietary polymer	Blackspot seabream (*Pagellus bogaraveo*)	Effect on fish fitness, increased mortality and oxidative stress	[80]
India	PP (11.86–44.62 µm)	Zooplankton (*Artemia salina*)	Increased mortality	[81]
India	PVC	Fish (*Etroplus suratensis*)	Decrease in both white and blood cells, decrease in growth, behavior change occurs	[82]
China	PS (150 µm)	Microalgae (*Chlorella vulgaris*)	Inhibitory effects on the growth	[83]
Poland	PE fragments (149 ± 75 µm), PAN fibres (47 ± 22 µm), tire wear particles (253 ± 142 µm)	Aquatic macrophyte (*Elodea canadensis*)	Inhibits MP adsorption and chlorophyll content in plants	[84]
Slovenia	Nano PS	Aquatic invertebrate (*Daphnia magna, Dapnia pulex*)	Lack of potential for toxic hazards	[85]
Slovenia	PE (4–12 µm)	Floating macrophyte (*Lemna minor*)	MP adsorption to plants and reduced root length	[86]
China	PAN fibers (329.3 ± 164.1 µm)	Goldfish (*Carassius auratus*)	Decreased food intake and the coughing behavior of fish increased significantly	[87]
Korea	PA	Crucian carp (*Carassius carassius*)	Inhibition of acetylcholinesterase activity in liver, gills and intestines	[88]
Korea	PE powder (34–50 µm)	Korean bullhead (*Pseudobagrus fulvidraco*)	Negative effects on hematological parameters, plasma composition and antioxidant response	[89]

[a] Polyethylene (PE), acrylonitrile butadiene styrene (ABS), polyvinylidene difluoride (PVDF), polylactic acid (PLA), polystyrene (PS), polyacrylonitrile (PAN), polyvinyl chloride (PVC), polypropylene (PP), polyamide (PA)

of polymethyl methacrylate (PMMA) MP could be effectively removed by earthworms [92]. Earthworms remove MP from soil by ingesting MP, which is supported by the increased amount of MP in the earthworms' intestine [92, 93]. This can eventually impose toxic effects on earthworms as indicated in Table 1. Also, different microbial species have been studied for their MP degradation potentials [94–96]. The MP degradation varied by microbial species and MP types (Table 3). Some studies investigated the microbial degradation pathways of MP [96]. Despite increasing research on the microbial degradation of MP, this field is still in its early stages, and more studies are needed to explore potential applications of microorganisms for MP degradation. Plants can absorb and adsorb MP in soil depending on the size of MP, thus, phytoremediation can be applied for removal of MP in soil. Phytoremediation is more suitable for shallow soil, and small-sized plants (i.e., < 10 feet) are efficient in the rhizosphere remediation [97]. Previous study showed that lettuce roots adsorbed MP stabilizing MP in soil [98]. Although MP in soil can be biologically removed using different organisms, the MP removal efficiency is relatively low (Table 3). In addition, potential toxic effects on the organisms used in MP removal need more investigation.

Apart from biological technologies, other technologies such as plasma treatment, adsorption, and separation based on saturated fat phase transition have been explored to remove MP in soil. Previous studies used dielectric barrier discharge (DBD) plasma to remove MP in soil, and the plasma treatment could remove MP with a wide range of sizes with high removal efficiency (> 96.5%) [99, 100]. The main degradation product was CO_x gas, suggesting almost complete oxidation of MP [99]. Also, MgO-modified peanut shell biochar could effectively remove MP in soil by adsorption [101]. Although adsorption does not remove MP from soil, it can reduce the mobility of MP in soil. In another study, coconut oil was used to separate five types of MPs (LDPE, PP, PS, polyethylene terephthalate (PET),

Table 3 Technologies for removing microplastics (MP) in soil

MP type[a]	Removal technologies	Scale	Removal mechanism	Evidence for removal	References
PMMA	Bioremediation using earthworms (*Eisenia fetida*)	Lab	MP uptake by earthworm	95.4–99.5% (100 µm), 86.6–95.7% (1 µm)	[92]
LDPE, PLA, PBAT	Bioremediation using Earthworms (*Lumbricus terrestris*)	Lab	MP uptake by earthworm	Significant increase in the amount of MP in the worms' internal organs	[93]
LDPE, PS, PU	Bioremediation using soil microorganisms (*Penicillium* sp.)	Lab	Biodegradation of MP	28.3% (PU), 8.4% (PS), 3.5% (LDPE)	[94]
PE, PP	Bioremediation using soil microorganisms (*Lysinibacillus* sp.)	Lab	Biodegradation of MP	9% (PE), 4% (PP) over 26 d	[95]
PU	Bioremediation using soil microorganisms (*Pseudomonas capeferrum* TDA1)	Lab	Biodegradation of MP	Mineralization of degradation intermediates (4,4′-methylenedianiline, 2,4-toluene diamine) of MP	[96]
PE	Phytostabilization	Lab	Phytostabilization through adsorption of MP	MP adsorption on lettuce roots confirmed by scanning and transmission electron microscopy	[98]
PE, PP, PS, PVC	Dielectric barrier discharge plasma treatment	Lab	Removal of MP by reactive oxygen species	96.5% (50–1500 µm)	[99]
PS	Dielectric barrier discharge plasma treatment	Lab	Removal of MP by reactive oxygen species	98.7% (1.5–600 µm)	[100]
PS	Remediation using adsorbents (MgO-modified peanut shell biochar)	Lab	Formation of biochar-MP heterogeneous aggregates through adsorption of MP on biochar	75.5%	[101]
LDPE, PP, PS, PET, PTFE	Separation based on saturated fat phase transition using coconut oil	Lab	Separation of MPs from soil by exploiting the phase transition properties of saturated fats	100%	[102]
PLA	Soil microbial electrochemical system	Lab	Acceleration of MP degradation by bioelectric fields	8.94% MP mass loss after 120 d, ~ 3 times greater loss with bioelectric field	[103]

[a] Polyethylene (PE), low density polyethylene (LDPE), polyethylene terephthalate (PET), polylactic acid (PLA), polystyrene (PS), poly tetrafluoroethylene (PTFE), polybutylene adipate terephthalate (PBAT), poly methyl methacrylate (PMMA), polypropylene (PP), polyvinyl chloride (PVC), polyurethane (PU)

poly(tetrafluoroethylene) (PTFE)) from soil based on saturated fat phase transition [102]. While the saturated fat phase transition technique can be used to separate MP from soil for the subsequent analysis purposes, its application potential as a MP removal technology is yet to be explored. When soil microorganisms and electrochemical system are combined, microbial biodegradation of MP can be enhanced [103]. For example, the reduction in PLA MP mass was about three times greater in the presence of bioelectric field than in the absence of it [103]. Other technologies such as soil washing and thermal desorption can also be used to remove MP in soil; however, these technologies have many challenges (e.g., high colst, seconday pollutant generation, adverse effects on soil quality) to overcome [104, 105]. In addition, conventional technologies for removal of contaminants in soil have limited effectiveness for removal of MP in soil, and combination of different technologies has been suggested for better MP removal efficiency [106]. The efficiency of MP removal by microbial degradation is low (Table 3), so technologies such as physical removal or chemical digestion can be combined with bioremediation [106]. Since studies on removal of MP in soil have largely been conducted at the laboratory scale, their practical feasibility is yet to be determined with further studies involving pilot studies and field applications.

Removal technologies of MP in water

Table 4 summarizes existing technologies that can be used to remove MP in water. Compared to the MP removal technologies for soil, a wide range of technologies that have been developed to remove particulates in water can be applied for MP removal in water. Different countries have been developing MP removal technologies for application to water treatment facilities (e.g., sand filtration and chlorination in Israel, membrane disc filter in South Korea, rapid sand filter/membrane bioreactors (MBR)/membrane disc filter in Finland, and ultrafiltration in Thailand) [108, 144–146]. Consequently, these MP removal technologies have been

Table 4 Technologies for removing microplastics (MP) in water

Removal technologies	Description of the technologies	References
Ultrafiltration	• Can remove particulates, macromolecules, and MP with pore sizes between 1 and 100 nm • Economical method due to low energy consumption, high separation efficiency, and compact plant • Not specifically designed for MP removal in wastewater • Previous studies reporting high removal rates for polyethylene MP • Lack of data on the effect of physicochemical properties of various types of MP on removal efficiency	[107–109]
Dynamic membrane (DM) filtration	• Based on the formation of a cake layer acting as a secondary membrane/barrier when particles and other contaminants in wastewater are filtered through the support membrane • The cake layer can remove suspended solids, colloids, microorganisms, and MP particles in wastewater • Uses relatively inexpensive materials (such as mesh, non-woven fabric, and woven filter cloth, and stainless-steel mesh) compared to existing membrane filters • No additional chemicals or other contaminants are introduced • Previously studied for removing particulates in wastewater • No research on MP removal using DM technique	[107, 110, 111]
Reverse osmosis (RO) filtration	• Filter contaminant under high pressure (10–100 bar) using a semi-permeable membrane • Applied in seawater desalination, food production, and sewage treatment • MP removal occurs through size exclusion and hydrophobic interactions with the membrane • Membrane defects are frequent in RO equipment, despite effective MP removal	[107, 112–116]
Membrane bioreactor (MBR)	• Integrates catalysis, complexation, biodegradation, and membrane separation processes using biological catalysts (bacteria, enzymes) • Effectively reduces MP, total suspended solids (TSS), turbidity, biological oxygen demand, and pathogen levels • Different compartments are separated by membranes in the MBR, maintaining phase separation • Safe, eco-friendly, and easily combinable with other processes • Considered the most efficient process for MP removal in water • Fouling management and improvement are necessary due to membrane contamination and damage	[107, 117–123]
Sand filtration	• Mainly used in drinking water treatment plants to remove MP by trapping it between sand grains or attaching it to the surface of the sand grain • Consists of different layers of medium like sand, gravel, and quartz, making it effective in removing large MP from water • Utilized in the treatment process of plastic recycling industrial wastewater	[124, 125]
Microfiltration	• Filtering pollutants using membranes smaller than 1 µm • Ceramics can replace existing polymer membrane filters • Generally made of titanium dioxide, zirconium dioxide, and aluminum oxide, it has excellent chemical and mechanical durability • Can withstand backwash pressure and resist detergents • Lack of research on MP removal using ceramic membranes	[117, 126, 127]
Activated carbon filtration	• Effective in removing organic pollutants • Powdered activated carbon (PAC) removes trace contaminants by attaching them to its surface • Clogging issues are common in column-based MP removal using PAC • Granular activated carbon (GAC) can be used to solve the clogging problem	[128–131]
Coagulation and Flocculation	• Destabilizes and aggregates MP in water using coagulants • MP removal efficiency depends on the type of coagulant used • Simple to operate and cost-effective • Influenced by variations in water quality and pH levels • Risk of secondary contamination from coagulant residues	[132–135]
Electrochemical coagulation	• Releases metal ions into water through electrolysis using a metal electrode • Simple, eco-friendly, less sludge production, low cost, energy efficient, and easy to automate • Pollutant removal efficiency depending on operating parameters like current intensity, electrolysis time, sample pH, and electrode spacing	[135–138]
Bioremediation	• Eco-friendly technique using aquatic eukaryotes, animals, seaweed, and macrophytes to remove MP from wastewater • Requires more cost and management due to reliance on biological activity • Lack of studies on removal efficiency and effects in field conditions compared to laboratory studies	[97, 128]
Dissolved air floating (DAF)	• Removes suspended substances in water by attaching them to microbubbles that rise to the surface • Removal efficiency can be enhanced with the use of coagulants	[108, 139]

Table 4 (continued)

Removal technologies	Description of the technologies	References
Magnetic extraction	• Utilized to coagulate, precipitate, adsorb, and separate MP in wastewater • Cost-effective, eco-friendly, low energy consumption, minimal risk of secondary contamination, and suitability for large-scale implementation • More effective removal of smaller-sized MP compared to other removal methods	[127, 140]
Advanced oxidation process (AOP)	• Used to remove non-degradable contaminants in water by generating OH radicals for degradation or to change the physicochemical composition of MP for degradation • Only partially oxidizes MP reducing particle size, but potentially creating smaller MP particles • Can increase surface tension and hydrophilicity of MP, aiding in adsorption and solubility	[127, 141–143]

commercialized and widely utilized in various facilities, achieving an average removal efficiency of ~ 90% [124, 129, 147–149].

Filtration can efficiently remove MP by size exclusion. Various filtration technologies such as ultrafiltration, dynamic membrane (DM) filtration, reverse osmosis (RO) filtration, sand filtration, microfiltration, activated carbon filtration, granular activated carbon (GAC), and MBR have been used to remove MP in water [112, 132]. Technologies including advanced oxidation processes (AOP), coagulation and flocculation, and dissolved air flotation (DAF) have been reported to achieve significantly high MP removal efficiencies [128]; however, research on the potential of secondary contamination and toxicity during the removal processes and their applicability under various conditions (e.g., different size, density, and shape of MP) remains insufficient [128, 141, 142]. The potential of secondary contamination can be reduced with technologies like electrocoagulation and magnetic extraction [140]. Bioremediation technologies include biofiltration, bio-consumption, biodegradation, and processes that combine biofiltration with other treatment methods [97, 128]. Bioremediation has been considered as a safe and sustainable treatment solution; however, further research is necessary due to relatively high costs and challenges in maintenance and management, as well as limited knowledge regarding the impacts of MP on target organisms [97].

Table 5 summarizes recent studies on removal of MP in water. Most of the studies reviewed in this review carried out lab-scale studies on different technologies for removal of MP in different wastewaters (real/artificial) (Table 5). Within the scope of our investigation, no studies were found on MP removal in natural aquatic environments, such as seas and rivers, outside of facility-based or laboratory settings. The commonly used types of MP in these studies include PE, PS, and PP, and the average MP removal efficiency reported across the studies was relatively high at 90.4%, with minimal variation in removal efficiency among the different technologies (Table 5). Also, more studies were available on membrane filtration and physicochemical treatment technologies than other technologies (Table 5).

MP removal with filtration technologies

Recently, various filtration technologies have been studied as shown in Tables 4 and 5. Depending on the MP type and filtration technologies, the MP removal efficiencies of 70–100% have been reported (Table 5). Apart from membrane-based filtration, media filtration like activated carbon filtration and sand filtration has been efficiently used to remove MP in water (Tables 4 and 5). For example, the $ZnCl_2$ modified activated carbon was about six times more efficient than untreated activated carbon for MP removal, and the primary removal mechanisms of the modified activated carbon were pore filling and electrostatic interaction with a spontaneous physical adsorption process by entropy [152]. Since the manufacturing cost of GAC is high, biochar has been used as an alternative to remove MP [131]. More than 90% of 10 µm MP has been removed with biochar, and it was proposed as a low-cost and high-efficiency system [131]. Some studies also combined different technologies to remove MP in water. For instance, GAC was combined with ceramic membrane to remove MP in water [130]. Also, the ozonation combined with GAC filtration improved the MP removal efficiency by 17.2–22.2% compared to the conventional treatment of combined coagulation, sedimentation, and sand filtration [174]. In addition, compared to the conventional removal process consisting of pretreatment and primary and secondary treatment, the combined electro-coagulation, thermal regeneration, and GAC process was more effective in MP removal achieving 92.8% removal of MP with a smaller specific gravity than water and a size of 20–50 µm [175].

MP removal with coagulation and flocculation

Various coagulants, both chemical coagulants and biocoagulants, have been studied to remove MP in water through coagulation and flocculation processes (Table 5). Mixtures of chemical coagulants and biocoagulants have been used in the coagulation process to develop more eco-friendly and cost-effective

Table 5 Removal efficiency of microplastics (MP) from water using various technologies reported in recent studies

Removal method	MP type[a]	Sources of MP	Scale	Removal rate	References
Filtration technologies					
Ceramic microfiltration	PVC, PP, PE, PS	Wastewater	Lab	> 72%	[117]
Near dissolved organic matter microfiltration	PS, PE, PET	Artificial wastewater	Lab	91–100%	[126]
Sand filtration	PE, PP	Plastic recycling industrial wastewater	Lab	≤ 100%	[124]
Granular activated carbon	PE	Artificial wastewater	Lab	≤ 95.5%	[129]
Granular activated carbon with ceramic membrane	PE	Artificial wastewater	Lab	> 77.9%	[130]
Ceramic microfiltration	PET	Household wastewater	Lab	99.9%	[150]
Sand filtration with granular limestone	PS	Artificial wastewater	Lab	≤ 95.0%	[151]
Ultrafiltration	PE, PP	Wastewater	Pilot	100%	[147]
Activated carbon (non-modified) and $ZnCl_2$-modified activated carbon filtration	PS	Artificial wastewater	Lab	Better MP adsorption on $ZnCl_2$-modified activated carbon (2.376 mg g^{-1}) than that non-modified activated carbon (0.369 mg g^{-1})	[152]
Membrane bioreactor					
Membrane bioreactor with ultrafiltration membrane module	PP, PS, PET	Wastewater, Surface water, Ground water, Seawater	Lab	70–100%	[153]
Membrane bioreactor with ultrafiltration membrane module	25 MP types	Wastewater	Pilot	99.7%	[148]
Microfilm made of carbon nanoparticles	PE	Artificial cosmetic wastewater	Lab	95%	[149]
Coagulation and flocculation					
Coagulation using aluminum sulfate ($Al_2(SO_4)_3$), polyacrylamide, and *Moringa oleifera* seeds extract	PA, PS, PE	Artificial wastewater	Lab	93.0% (PA), 80.5% (PS), 28.9% (PE)	[154]
Coagulation using polyaluminum titanium chloride (PATC) composite coagulant	PS	Artificial wastewater, lake water	Lab	13% (PATC), 9.9% (polytitanium chloride), 7.7% (polyaluminum chloride)	[155]
Coagulation using ferrate	PE, PET	Surface water, distilled water (DI)	Lab	> 98% (surface water), 52.9% (PE, DI), 22.1% (PET, DI)	[156]
Coagulation using poly aluminum chloride	PE	Artificial wastewater	Lab	> 70% (13–48 µm)	[157]
Flocculation using chitosan and polyaluminum chloride	PET	Pure water	Lab	28.3% (polyaluminum chloride), 90% (chitosan & polyaluminum chloride)	[158]
Coagulation and flocculation using chitosan and alum	LDPE	Surface water from urban canal	Lab	92.1 ± 1.4% (0.090 mm), 21.2 ± 1% (0.3 mm), and 1.8 ± 0.4% (1 mm), 94.4% (combined MP, alum and chitosan), ~ 50% (combined MP, alum)	[159]
Coagulation using biocoagulant (algae *chlorella vulgaris*)	PE	Artificial wastewater	Lab	≤ 84%	[160]
Electrochemical coagulation					
Electrochemical coagulation	LDPE	Rainfall runoff from agricultural lands	Lab	98%	[161]

Table 5 (continued)

Removal method	MP type[a]	Sources of MP	Scale	Removal rate	References
Electrochemical coagulation	PA	Artificial wastewater	Lab	90.9% (Fe anode-Al cathode), 88.4% (Fe–Fe), 86.9% (Al–Fe), 83.7% (Al–Al)	[162]
Electrochemical coagulation	PS	Artificial wastewater	Lab	90.7% (0–75 µm), 93.6% (75–150 µm), 94.6% (150–300 µm)	[163]
Electrochemical coagulation, Al/Fe-graphene-electrocoagulation	PP, PS, PET	Artificial wastewater	Lab	86% (PET, Fe-graphene), 92% (PET, Al-graphene), 90% (PS, Fe-graphene) 94% (PS, Al-graphene), 80% (PP, Al-graphene and Fe-graphene)	[164]
Dissolved air flotation					
Dissolved air flotation, 0.5 g L^{-1} NaCl added	PE	Artificial wastewater	Lab	77–95% (with NaCl), 24–38% (without NaCl)	[165]
Dissolved air flotation, microbubble flotation	PE, PES, PAN, PA, PP	Laundry wastewater	Lab, Pilot	> 90% for PE, PP, PES, and PA, 82% for PAN	[166]
Dissolved air flotation (DAF), nanobubble flotation (NBF)	PS	Sea water	Lab	81.1% (DAF, 10 µm), 85.7% (DAF, 40–50 µm), 88.2% (NBF, 10 µm), 86.3% (NBF, 40–50 µm)	[167]
Ozonation					
Ozonation, wet oxidation	PE, PP, PS, PA, PET, PVC	Wastewater	Lab	86.3 ± 1.7% (oxidation), 45.2 ± 1.3% (ozonation)	[168]
Ozonation	PE, PP, PS, PVC	Wastewater	Lab	MP surface area loss by 1.3–26.7%	[169]
Magnetic separation					
Magnetic separation, magnetic filter and magnetic medium carrier Fe_3O_4	PVC	Artificial wastewater	Lab	≤ 100%	[140]
Magnetic separation, magnetic ZIF-8 nanocomposite	PS	Artificial wastewater	Lab	≥ 98%	[169]
Magnetic separation, rotating magnetic field and maifanite	PS	Artificial wastewater	Lab	Maximum of 98.5%	[170]
Biofiltration					
Biofiltration, blue mussels (i.e., *Mytilus edulis*)	PS, PE, PP	Artificial seawater, Seawater	Lab, Field, Modelled	66% (3 h, 300 mussels, lab), 239.9 ± 145.9 MP particles (24 h, 5 kg mussels, field), 4% (modelled)	[172]
Biofiltration, Mediterranean tube-dwelling polychaete (*Sabella spallanzani*), mollusk bivalve (*Mytilus galloprovincialis*), white sea-squirt (*Phallusia mammillata*), calcareous sponge (*Paraleucilla magna*)	PS	Artificial seawater	Lab	3.48 L h^{-1} DWg^{-1} (*S. spallanzanii*), 7.11 L h^{-1} DWg^{-1} for (*M. galloprovincialis*), 2.95 L h^{-1} DWg^{-1} (*P. mammillata*), and 0.95 L h^{-1} DWg^{-1} (*P. magna*)	[173]

[a] Polyethylene (PE), low density polyethylene (LDPE), polyethylene terephthalate (PET), polyester (PES), polylactic acid (PLA), polyacrylonitrile (PAN), polystyrene (PS), polypropylene (PP), polyvinyl chloride (PVC), polyamide (PA), poly methyl methacrylate (PMMA)

coagulation process [154, 158–160]. For instance, when chitosan was added to polyaluminum chloride, the removal efficiency of PET MP from pure water was increased by more than three times (~90%) compared to when only polyaluminum chloride was used (28.3%) [158]. Similarly, the removal of LDPE MP was greater in the presence of both alum and chitosan (94.4%) than in the presence of only alum (~50%) [159]. Also, composite coagulants have been used to enhance the MP removal efficiency [155]. Interestingly, the MP removal was greater in surface water with natural organic matter than in distilled water, suggesting the interaction between MP and natural organic matter [156]. Coagulants required in the coagulation process can also be electrochemically generated and used in the coagulation process (i.e., electrochemical coagulation). Previous electrochemical coagulation studies reported the MP removal efficiency of greater than 80% (Table 5). The electrode combinations used in the electrochemical coagulation can affect the MP removal efficiency [162]. Also, the MP removal efficiency differed by the MP size [163].

Coagulation removes MP by settling them at the bottom of the reactor, while DAF removes MP by floating them on water. Previous studies used sodium chloride to better separate MP [165] and used different bubble sizes to separate MP from water [166, 167]. Previous study reported that the removal efficiency of PE, PES, PA, and PP MP in laundry wastewater using microbubble floatation were over 90% under the optimized conditions, while it was 82% for PAN MP [166]. Another study reported the improved PS MP removal efficiency from seawater (86.3–88.2%) by using nanobubble flotation when compared to the conventional DAF process (81.1–85.7%) [167].

Other MP removal technologies

Other technologies such as ozonation, magnetic separation, and biofiltration have also been explored in previous studies (Table 5). Compared to ozonation (45.2 ± 1.3%), wet oxidation (86.3 ± 1.7%) was more effective in MP removal [160]. Ozonation removed MP through entrainment of MP by gas bubbles in an open reactor, while wet oxidation removed MP through chemical degradation in a closed reactor [168]. Magnetic extraction technique separates and removes MP by using magnetic nanoparticles [140, 170]. With magnetic nanoparticles, MP removal efficiencies greater than 98% were achieved in previous studies [140, 170]. When maifanite (clay mineral particles affected by a magnetic field) was used with a rotating magnetic field, collisions between particles were increased enhancing the MP removal [171]. With biofiltration, aquatic organisms such as blue mussels (i.e., *Mytilus edulis*), tube-dwelling polychaete (*Sabella spallanzani*), mollusk bivalve (*Mytilus galloprovincialis*), white sea-squirt (*Phallusia mammillata*), and calcareous sponge (*Paraleucilla magna*) were used to study the MP removal potential [172, 173].

Overall, previous studies on the MP removal in water explored various technologies to enhance MP removal efficiency, reduce the removal costs, and reduce generation of secondary pollutants. Most technologies including filtration, coagulation, DAF, magnetic extraction, and biofiltration are technologies to separate MP in water from water and they are not necessarily technologies to degrade MP. Thus, separated MP still need to be treated to either completely degrade them or reuse them in other ways.

Recommendations for future studies

Research on MP removal has been attracting increasing attention recently. Many existing studies have addressed the importance of MP pollution control in the environment and investigated different technologies for MP removal in soil and water with greater emphasis on the water environment. Although contaminated soil and water environments need to be treated with appropriate technologies, source control is a better management for MP in different environmental media, since many sources contribute to MP in both soil and water environment. With MP removal technologies, most studies used a single technology to remove MP with certain characteristics in water or soil and reported reasonable removal efficiencies; however, the characteristics of MP in the real-world and the environmental conditions are likely to be more complicated, which may result in lower MP removal efficiencies. Also, previous studies have been largely carried out on a lab scale, so more studies at pilot scale or field scale are required to properly test the feasibility of each developed technology. Therefore, more studies reflecting the real-world settings are necessary. Although limited, some field research and case studies on removal of MP in water have been carried out. A field experiment in lake areas reported the potential of using freshwater reeds to remove MP by accumulation [176]. A case study in Surabaya City, Indonesia showed a MP removal efficiency of 54–76% by conventional methods such as coagulation, sedimentation, and filtration in drinking water facilities [177]. In another case study conducted at a wastewater treatment plant in Caravaca de la Cruz, Spain, the MP removal efficiency of 89–95% has been observed over a one-year period [178].

Various technologies have been developed to remove MP in soil and water environments; however, they are still in their early stages. This paper reviewed the technologies for MP removal from soil and

these technologies used different soil organisms (e.g., earthworms, microorganisms, and plants) to biologically separate and/or degraded MP, plasma to chemically degrade MP, adsorbents to physically stabilize MP, and oils to physically separate MP based on saturated fat phase transition. With the technologies for MP removal from water, filtration, coagulation, DAF, magnetic separation, and biofiltration have been reviewed. The MP removal technologies for water focus on separating MP from water rather than degrading them, while the MP removal technologies for soil have removal mechanisms of both separation and degradation. Thus, more MP degradation technologies need to be developed, and the post-treatment and reuse of the separated MP need to be considered in future studies.

Since there are more options for MP removal from water than soil, more technologies for soil MP removal are also required. In particular, when soil is in use (e.g., agricultural soil), non-disturbing in-situ technologies need to be applied to remove MP. With water MP removal technologies, most studies target MP in wastewater and drinking water treatment plants. But MP are also present in natural waters, which contain other materials (e.g., natural organic matter) that can interfere with MP removal, so technologies for treating MP in natural waters are also required. For both soil and water environments, no standardized methods for quantifying MP contamination and removal efficiency are available yet. Thus, standardized methods need to be prepared to better manage MP problems in soil and water environments. Furthermore, the MP removal technologies need to be cost-effective and eco-friendly for real-world applications.

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Ji Won Yang: conceptualization, data curation, formal analysis, visualization, investigation, writing—original draft, writing—review and editing. Chanhyuk Park: conceptualization, formal analysis, writing—original draft. Eun Hea Jho: conceptualization, formal analysis, visualization, supervision, project administration, funding acquisition, writing—original draft, writing—review and editing.

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Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. EHJ is an editor of Applied Biological Chemistry.

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