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REVIEW ARTICLE

Research progress on distribution, sources, identification, toxicity, and biodegradation of microplastics in the ocean, freshwater, and soil environment

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HIGHLIGHTS

- Microplastics are widely found in both aquatic and terrestrial environments.
- Cleaning products and discarded plastic waste are primary sources of microplastics.
- Microplastics have apparent toxic effects on the growth of fish and soil plants.
- Multiple strains of biodegradable microplastics have been isolated.

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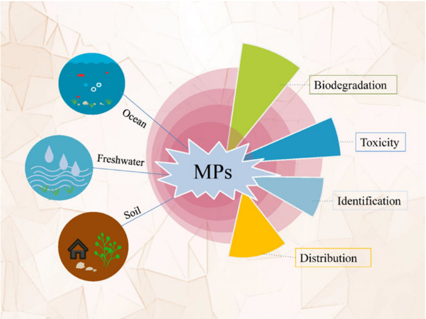
GRAPHIC ABSTRACT



ABSTRACT

Microplastics (MPs) are distributed in the oceans, freshwater, and soil environment and have become major pollutants. MPs are generally referred to as plastic particles less than 5 mm in diameter. They consist of primary microplastics synthesized in microscopic size manufactured production and secondary microplastics generated by physical and environmental degradation. Plastic particles are long-lived pollutants that are highly resistant to environmental degradation. In this review, the distribution and possible sources of MPs in aquatic and terrestrial environments are described. Moreover, the adverse effects of MPs on natural creatures due to ingestion have been discussed. We also have summarized identification methods based on MPs particle size and chemical bond. To control the pollution of MPs, the biodegradation of MPs under the action of different microbes has also been reviewed in this work. This review will contribute to a better understanding of MPs pollution in the environment, as well as their identification, toxicity, and biodegradation in the ocean, freshwater, and soil, and the assessment and control of microplastics exposure.

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1 Introduction

Massive production and use of plastic products bring convenience to people while leading to the accumulation of plastic pollutants in the environment (Weithmann et al., 2018). In total, 80% of plastic wastes can accumulate in landfills or be released into natural environments (Tourinho et al., 2019). These large discarded plastic pieces break into tiny pieces less than 5 mm in diameter, known as MPs. MPs are difficult to degrade in the natural environment due to their physical and chemical characteristics. In other words, it can lead to possible impacts on ecosystem. Microplastic pollution has gradually become a global problem and attracted much attention from scientists (Yuan et al., 2020).

MPs can be divided into two groups. Primary MPs are synthesized in industrial production, and secondary MPs are generated by physical and environmental degradation. As shown in Fig. 1, primary MPs include household products, such as fiber in clothing, plastic beads in cosmetics, toothpaste, facial cleansers (Corradini et al., 2019), and medical products that can be used as drug carriers (Carr et al., 2016). Secondary MPs are small plastic particles or fragments that plastic waste undergo physical and chemical factors such as weathering, oxygen, temperature, and ultraviolet light (Li et al., 2020a). Besides, sewage treatment plants (WWTPs) are not effective in intercepting all plastic debris, making WWTPs an MPs source (Sun et al., 2019; Li et al., 2020a). MPs are small particle size, diverse shapes, difficulty in degradation and significant potential effects (Cheung et al., 2018). MPs are extremely widespread and can be detected in soil sediments and aquatic environments such as oceans, lakes, rivers, and even aquatic products including salt and seafood (Yang et al., 2015; Lei et al., 2018). Most observed polymer types are polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinylchloride (PVC) and polyethylene terephthalate (PET) (Koelmans et al., 2019). Because of the density, PE, PP, PS are more likely to float, and PVC and PET are more likely to sink in water. The distribution of MPs is also influenced by other factors such as flowrate, water quality, obstruction structure, coastline shape, and biological uptake and digestion (Alomar et al., 2016; Ballent et al., 2016; Wang et al., 2017). Therefore, the distribution of both the aquatic system and soil environment need to be discussed for increasing understanding of MPs.

MPs are easily ingested by aquatic organisms and accumulate in the body (Wang et al., 2020), causing potential damage to living biology. Ingestion of MPs could cause blockages throughout the fish digestive system and lead to structural and functional deteriorations in gastrointestinal tracts (Wright et al., 2013; Peda et al., 2016). MPs were also reported to absorb harmful substances such as heavy metals in the environment and concentrate hydrophobic pollutants (Wang et al., 2019). More seriously, MPs could bring potential severe toxic effects to human beings via food chain transmission (Li et al., 2020a). Thus, MPs in the environment leads to possible threats to biota and public health (Rillig et al., 2017; Gouin et al., 2019).

These tiny, ubiquitous plastic particles bring profoundly

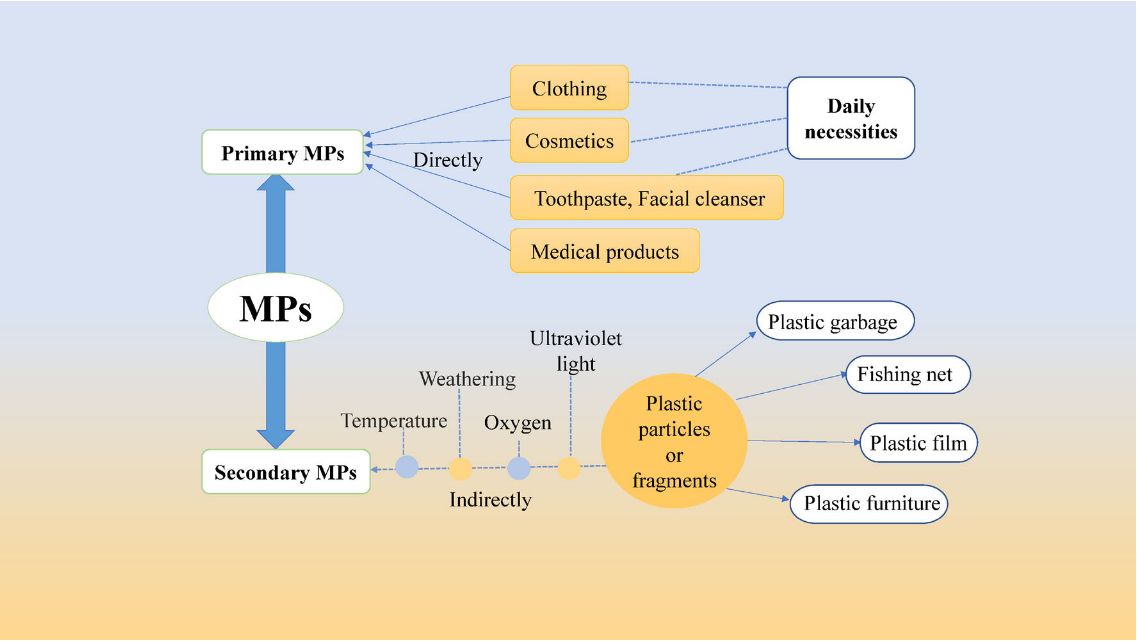

Fig. 1 Main sources of primary and secondary microplastics in the environment.

negative consequences and represent one of the most significant environmental challenges. The increasing problem of MPs pollution has attracted attention worldwide (Banerjee and Srivastava, 2012; Meng et al., 2020). To control MPs pollution, microbeads are banned from cosmetic and personal care products in the USA (Meng et al., 2020). Products containing microbeads were also banned in European countries. Moreover, San Francisco also banned plastic grocery bags and plastic water bottles (Sharma and Chatterjee, 2017). MPs pollution is controlled by banning or charging for plastic shopping bags in California, Ireland and Scotland (Sharma and Chatterjee, 2017). The Indian government banned the production, dumping and sale of plastic bags that are less than 20 microns thick (Sangale et al., 2019). These policies will effectively reduce MPs pollution.

Over the years, there have been many reports from different regions of the world describing the association of MPs pollution in ocean, freshwater and soil environment, which brought severe toxic effects to animals and human beings (Browne et al., 2011; Wardrop et al., 2016; Wang et al., 2020). This review comprehensively summarizes the current global MPs pollution situation. According to published articles, distribution and sources of MPs in ocean, freshwater and soil are summarized in detail. Moreover, this review focuses on MPs toxicity and identification. The potential toxicity of MPs and the shortcomings of detection methods were analyzed. Especially, effective bacterial and fungal strains of biodegradable MPs were listed. Based on the literature review, the effective strains were mainly isolated from ocean and soil environment, but the freshwater environment was deficient.

2 Microplastic pollution in the ocean environment

Research on MPs in ocean environments started early (Carpenter et al., 1972) and attracted broad attention all over the world. Because of its widespread distribution, wide sources and small size, it is difficult to detect the presence of MPs and adverse effects (Shim and Thomposon, 2015). At present, physical features are commonly identified by stereoscopic microscope and scanning electron microscope (SEM) (Mahon et al., 2017), and chemical characteristics of MPs are mainly based on Fourier transform infrared (FTIR) spectroscopy and Raman spectroscopy (Lenz et al., 2015). These types of equipment effectively improve the accuracy of microplastic identification. A study suggested that small MPs made them easily available for ingestion by a variety of organisms with great consequences in the ocean environment (Auta et al., 2017). To control MPs pollution, some bacteria and fungi strains were isolated and reported for degradation of MPs in the ocean (Yuan et al., 2020), which will play a positive role in the control and management of MPs pollution.

2.1 Distribution and sources of microplastic pollution in the ocean environment

It was estimated that about 4.8–12.7 million tons of traditional plastic waste enter the ocean environment each year, and this plastic waste creates approximately 5.25 trillion floating particles of MPs in the global oceans (Eriksen et al., 2014; Jambeck et al., 2015). In recent decades, MPs have been reported to be detected in the global ocean environment, including the North Atlantic, South Atlantic, South Indian, North Pacific, South Pacific and even in Antarctic and Arctic waters (Eriksen et al., 2014; Sharma and Chatterjee, 2017). It shows that microplastic pollution is no longer just a national or regional problem but a global one. Areas with high MPs levels are the North Pacific Ocean and its marginal seas, such as in the western and southern coasts of Korea (Eriksen et al., 2014; Shim and Thomposon, 2015). It is closely related to the degree of industrialization and population density of the surrounding coastal countries (Browne et al., 2011). Also, MPs were reported to be contaminated in the South China Sea, resulting from human fishing and industrial activities (Cai et al., 2018b). MPs were also reported on seawater and fish samples in Hainan province in China. Each fish contained an average of 3.1 microplastic particles. Ingested MPs in fish were mainly fibers, and most MPs were transparent or blue (Nie et al., 2019). The sea area is close to Guangdong and Hainan provinces, with a large population and high demand for plastic production. High concentrations of MPs may be associated with high demand for plastic products (Cai et al., 2018b).

Plastic processing plants near the coast are the primary source of MPs in seawater (Hidalgo-Ruz et al., 2012). Microplastic particles are found in individual care products, cleaning products, and washing synthetic clothes (Murphy et al., 2016; Auta et al., 2017). These particles may enter the ocean environment through Wastewater Treatment Plants (WWTPs) (Murphy et al., 2016). Although the removal efficiency of MPs in some WWTPs was relatively high (Leslie et al., 2017), treating a large amount of wastewater every day may also discharge a large number of MPs. It can exacerbate the level of microplastic pollution and place an even greater burden on the ocean ecosystem. For example, a report of 17 sewage treatment facilities (Mason et al., 2016) showed that each treatment facility is expelled from an average of more than 4 million particles per day. This increased concerns about the direct discharge of MPs from urban sewage into the water environment (McCormick et al., 2014; Mason et al., 2016). Besides, sea recycling ports, landfills and sewage sludge are also possible sources of microplastic pollution in the ocean environment (Alomar et al., 2016; Auta et al., 2017).

2.2 Separation and identification of microplastic in the ocean environment

The separation and analysis methods of MPs are similar in seawater and freshwater. Several detection methods for MPs were reported. For the pretreatment of MPs, NaCl, $ZnCl_2$, NaI, H_2O_2 solution with a volume fraction of 30% and Fenton reagent are applied (Cole et al., 2014; Tagg et al., 2016; Li et al., 2018; Yuan et al., 2019). In general, the extraction and analysis process includes separation, purification, sieving, and identification procedure. The most common MPs density was at the range of 0.8–1.4 g/cm^3 (Gu et al., 2020). In the initial extraction procedure of MPs, density-based separation methods were usually considered (Hidalgo-Ruz et al., 2012). Fenton reagent can decompose organic compounds rapidly in a short time without influence on the characteristics of MPs (Tagg et al., 2016). It is an efficient reagent for removing organic compounds and suitable for sample processing (Hurley et al., 2018). Fenton reagent is universally applied for water sample purification, and it is recommended by the national oceanic and atmospheric administration (NOAA) for analysis of MPs in ocean environments (Sun et al., 2019).

After sieving through sieves of variable mesh sizes, larger microplastic particles with the size of 1–5 mm, color, shape and size can be directly obtained by microscope. The residue on filter paper and other processed samples were monitored by stereomicroscope. However, it is easy to be influenced by different people, which leads to errors and misjudgment (Hidalgo-Ruz et al., 2012). Some particles or other substances similar to MPs require further confirmation by scanning electron microscope (SEM). SEM has high magnification characteristics, a wide field of vision and stereoscopic imaging (Mahon et al., 2017). The structure of uneven surfaces of various samples can be observed (Cai et al., 2018a).

Obviously, it is not enough to analyze MPs in the environment only by stereomicroscope or SEM due to complex composition. Therefore, the MPs' composition should also be analyzed. In many analysis processes, MPs are first visually measured and measured under a stereoscopic microscope. The color, number and size of MPs are recorded, and then further identification is made by combining with Fourier spectrum or Raman spectrum analysis (Lo et al., 2018; Lares et al., 2019). The detection results can be used to correct the visual recognition (Yuan et al., 2019).

Fourier transform infrared (FTIR) spectroscopy and Raman spectrum (Lenz et al., 2015) are applied for accurately identifying the chemical composition of MPs by chemical bonds inside samples (Murphy et al., 2016). FTIR has the advantages of good reproducibility, and it is not affected by sample color, fluorescence and other conditions. It is suitable for MPs with a diameter of over 20 μm or samples containing strong polar functional group identification (Gu et al., 2020). Moreover, Focal Plane array-based (FPA) Reflectance micro-FTIR imaging is also applied to identify different types of treated MPs (Harrison et al., 2012). It is an effective method to detect MPs in water samples with more organic matters. Raman spectroscopy can be used to analyze microplastic particles (>1 μm) easily, quickly and without damage (Lares et al., 2019; Sun et al., 2019). Raman spectroscopy provided a better response of non-polar and revealed vibration information of the sample's molecular structure (Lenz et al., 2015). It has a more excellent spatial resolution, and the sample thickness does not influence identification (Lares et al., 2019). Also, it is not disturbed by atmospheric water and CO_2 (Elert et al., 2017). These two methods are often used in the analysis of solid samples.

In addition, there are several technologies under development, such as chromatography, thermogravimetric analysis, proton nuclear magnetic resonance spectroscopy (^{1}H NMR) and in situ identification (Möller et al., 2020). Pyrolysis gas chromatography-mass spectrometry (Pyr GC-MS) is a sensitive and mature method for qualitative and quantitative analysis of polymers in samples, but it is not suitable for bulk sample analysis (Fries et al., 2013; Nuelle et al., 2014; Hendrickson et al., 2018). Thermogravimetric analysis is limited in the analysis of MPs. PE and PP can only be analyzed when combined with other methods (David et al., 2018; Möller et al., 2020). Moreover, Pyr GC-MS and thermogravimetric analysis are destructive and can not provide the morphology and quantity of MPs, which is not conducive to subsequent analysis. ^{1}H NMR spectroscopy is also a qualitative and quantitative analysis method, but it has strict sample treatment requirements. The sample should not contain any organic matter (Peez et al., 2019). In a word, these techniques have not been widely used because of their destructiveness, high requirements on samples and uncertain test results. Continuing to measure is difficult unless these methods are improved.

2.3 Toxic effects of microplastic on marine life

It was reported that ingestion of MPs could cause symptoms such as reproductive complications, obstruction of digestive tract, reduced growth rate, and false satiation (Sutton et al., 2016). It posed a severe threat to the ocean environment and led to the death of millions of marine animals (Denuncio et al., 2011). Bivalves, such as oysters, are recommended as biological indicators of MPs contamination because of their feeding patterns and filtration capabilities, making them more prone to ingesting MPs in seawater (Li et al., 2016). In the previous report, oysters were exposed to 6 μm PS microbeads at three different concentrations (Thomas et al., 2020). After 80 days of continuous testing, PS microbeads were detected in intestines and digestive tubules. And the study proved that the highest dose of microbeads could increase mortality among juvenile oysters. Moreover, continued ingestion from the water environment could lead to the death of oysters. MPs were also reported to be detected in other marine organisms. MPs were first reported in marine invertebrate organisms sea turtles (Duncan et al., 2019). It was reported that MPs present in ocean environments were easily ingested by marine life due to their small size (Sharma and Chatterjee, 2017), which threatened marine life. In another study, 0.05, 0.5, and 6 μm fluorescently-labeled microbeads could be ingested by marine copepod *Paracyclopina nana* (Jeong et al., 2017). *P. nana* exposed to 0.05 μm microbeads suffered developmental delays and fecundity declines, while *P. nana* exposed to microbeads with a 0.5 μm diameter resulted in delayed molting. Moreover, the fecundity, oocyte size, hatching success rate and offspring survival rate of marine copepod *Tigriopus japonicus* (Lee et al., 2013), *Calanus helgolandicus* (Cole et al., 2015), and monogonont rotifer *Brachionus koreanus* (Jeong et al., 2016) were also decreased after exposing them to PS MPs for 12 days. The toxicity of MPs in cells was mainly triggered by oxidative stress reaction (Lee et al., 2013; Cole et al., 2015; Jeong et al., 2016), which led to cell damage and reduction in growth rate and reproductive capacity. MPs could distribute into global oceans via ocean currents and it was reported that MPs could be detected even in polar marine environments (Auta et al., 2017). Therefore, MPs could cause severe pollution to ocean environments and were easily sucked by sea creatures, which might cause a serious threat to the ocean ecosystem.

2.4 Biodegradation of microplastic in the ocean environment

Currently, it was reported that MPs could act as a carbon source to provide support for microbial growth and could be degraded by bacteria, fungi (Yuan et al., 2020). MPs could be degraded into CO_2, H_2O, or methane by bacteria in insect intestines and finally enter the ecosystem circulation (Kumari et al., 2019; Sánchez, 2020; Yuan et al., 2020). However, there was a lack of knowledge concerning microplastic removal, and it was not mature enough in practical application. Previously, an ocean bacterial strain *AIIW2* was isolated (Kumari et al., 2019) to degrade MPs. It was homologous with bacillus and showed different degradation capacities for different MPs. SEM detection results revealed that bacterial interaction increased roughness and deteriorated surface of plastics. The marine bacterial strain exhibited noticeable degradation effects on PVC and PE. Marine *Bacillus cereus* could degrade Nylon 6 and 66 at 35°C and pH of 7.5 (Sudhakar et al., 2007). Visible physical damage on fibers could be seen under a fluorescence microscope, and the weight of nylon 66 and 6 decreased by 7% and 2%, respectively. Moreover, it was reported that fungi could degrade MPs as well. Marine coastal waste was studied and two fungal strains exhibit degradation effects on high-density polyethylene were successfully isolated through in vitro screening (Sangeetha Devi et al., 2015). Isolated strains were identified as *aspergillus tubingensis VRKPT1* and *aspergillus flavus VRKPT2*. It was proved that fungi could be applied for MPs degradation. Strains with the ability to degrade MPs from ocean environments were summarized in Table 1. From the table, these strains were mainly marine fungus *Zalerion maritimum* (Paço et al., 2017), bacterial consortia *Agios Onoufrios* and *Kalathashad* (Syranidou et al., 2017), and *Kocuria palustris* (Syranidou et al., 2017), etc. However, these strains had a long experimental period and low degradation efficiency, with a minimum of 0.2%. It is necessary to optimize cultural conditions to increase degradation efficiency, and strains with higher efficiency still need to be isolated.

3 Microplastic pollution in the freshwater environment

MPs were also detected in globally freshwater at very high levels (Li et al., 2020a). Distribution and sources of microplastic pollution in the freshwater environment and adverse effects on freshwater organisms are similar to the ocean environment. However, the adverse effects of MPs on freshwater environments are controversial (Imhof et al., 2017; Li et al., 2020a). As in the ocean environment, strains for biodegradation of MPs were also isolated and reported for MPs control in freshwater.

3.1 Distribution and sources of microplastic in the freshwater environment

MPs were also distributed in freshwater systems around the world. High concentrations of MPs were detected in Asia, North America, Europe, and Australia (Zbyszewski et al., 2014; Li et al., 2020a), especially in Asia and America. The Great Lake and Lake Huron in the USA contain a high concentration of MPs, with concentrations of MPs at 1.6×10^7 particles/km^3 and 3.5×10^{11} particles/km^3 (Eriksen et al., 2013; Li et al., 2020a), respectively. The abundance of MPs reached 20264 particles/km^2 in a freshwater lake in northern Mongolia (Free et al., 2014). However, compared with the USA, Mongolia is geographically remote and sparsely populated. In addition to runoff, climate and other factors, there are deeper causes of microplastic pollution waiting to be explored. Also, we found that MPs are more likely to accumulate in stagnant water and freshwater downstream sediments (Meng et al., 2020), which may be influenced by the water's nutrient status and flow rate. Although we have found microplastic pollution in part of the freshwater environment, it is far from enough compared with ocean environments. The

Table 1 List of microplastic degrading microbial strains from ocean environment

Type of Strains	Name of Strains	Types of MPs	Action time (d)	Gravimetric weight loss (%)	Reference
Bacteria	*AIIW2*	PVC, PE	90	0.26±0.02, 1.0	Kumari et al., 2019
	Agios Onoufrios and *Kalathashad*	PE	180	19	Syranidou et al., 2017
	Bacillus cereus	Nylon 6 and 66	90	7, 2	Sudhakar et al., 2007
	Bacillus vesicualris	Nylon 6 and 66	90	4, 2	Sudhakar et al., 2007
	Kocuria palustris M16	PE	30	1	Harshvardhan and Jha, 2013
	Bacillus pumilus M27	PE	30	1.5	Syranidou et al., 2017; Harshvardhan and Jha, 2013
	Thalassospira povalilytica-11	PVA (Polyvinyl alcohol)	–	–	Nogi et al., 2014
	Bacillus subtilis H1584	PE	30	1.75	Harshvardhan and Jha, 2013
	Brevibacillus borstelensis	HDPE (High-density polyethylene)	30	11.4	Mohanrasu et al., 2018
	Bacillus sphericus, *Vibrio furnisii,*	Nylon	90	–	Sudhakar et al., 2007
	Bacillus sphericus GC subgroup IV, *Bacillus cereus subgroup A*	Thermally treated LDPE (Low-density polyethylene) and HDPE	365	19, 9	Sudhakar et al., 2008
		Unpretreated samples LDPE and HDPE	365	10, 3.5	
	Arthrobacter and *Pseudomonas*	HDPE	30	15	Balasubramanian et al., 2010
Fungi	*Zalerion maritimum*	PE	28	56.7±2.9	Paço et al., 2017
	Aspergillus tubingensis VRKPT1	HDPE	30	6.02±0.2	Sangeetha Devi et al., 2015
	Aspergillus flavus VRKPT2	HDPE	30	8.51±0.1	Sangeetha Devi et al., 2015
Macroalgae	*Alaria esculenta* and *Palmaria palmata*	PP, Nylon, PE	365	monthly average 0.39, 1.02, 0.45	Welden and Cowie, 2017

researches of MPs distribution in freshwater is relatively low, and many freshwater fields have not been studied and analyzed on MPs, such as South America and Africa (Li et al., 2020a).

Identifying sources of MPs is vital to mitigate the harmful effects on freshwater ecosystem. It was reported that most fibers were from daily laundry cleaning (Hartline et al., 2016). Because synthetic textiles are made up of many polyester products, they fall off during conventional laundry washing. It results in washing machine wastewater containing large amounts of microplastic fibers (Hernandez et al., 2017). As a result, wastewater discharge system was also a major source for MPs in freshwater environments (Eckert et al., 2018), similar to the ocean environment. Besides, similar cleansers ingredients were found in the Great Lakes region of North America (Eriksen et al., 2013). It indicated that plastic particles in individual daily life products might be one source of MPs pollution in freshwater environment. In addition, other social activities were important causes of MPs pollution in rivers and lakes. Industrial production activities contribute not only to microplastic pollution of ocean environment but also to freshwater areas. Large amounts of industrial resin particles and microspheres were found in lakes near industrial areas (Eriksen et al., 2013). Agricultural, industrial and fishing activities around Poyang Lake in China were also reported to blame for MPs' problem with the lake (Yuan et al., 2019).

3.2 Characteristics of microplastic in the freshwater environment

In previous literature, types, shapes, sizes and colors of MPs were identified. PE and PP were two major components of MPs in freshwater, followed by PET, PS, nylon, and PVC (Yuan et al., 2019; Zhang et al., 2020). First, PP and PE with low density make the two MPs float and migrate easily (Zbyszewski et al., 2014). Secondly, the output and utilization ratio of these two kinds of plastic products are higher. Therefore, it is urgent to find the treatment method of MPs to reduce PP and PE pollution to the environment. Shapes of MPs are commonly sorted by foamed, fibrous or linear, globular or granular, fragmental, and thin-films. Fibers and thin-films were the most common microplastic shapes (Meng et al., 2020). The size of freshwater MPs is usually 0.1–5 mm, and the small size makes MPs vulnerable to being consumed by aquatic organisms (Critchell and Hoogenboom, 2018). Besides, disposable plastic items could produce transparent MPs, while durable plastic products could generate colored MPs (Zhang et al., 2018). Unlike other common environmental pollutants, MPs exist in the environment as solids pollution, which has contrasting polymer types, shapes, sizes, and colors. MPs in freshwater ecosystems may correspond to these properties (Karbalaei et al., 2018).

3.3 Effects of microplastic on freshwater organisms

MPs were also detected in algae, fish, shrimp, and other freshwater organisms that might also bring toxic effects. MPs could hinder the photosynthesis of phytoplankton (Ding et al., 2017) and damage the intestinal and liver organs of animals. A recent study found that MPs could promote the synthesis of *Microcystis aeruginosa* (Feng et al., 2020). This kind of algae can cause cyanobacterial blooms in water, which has adverse effects on water ecology and human health. In the previous study, healthy adult zebrafish were exposed to different MPs concentrations in freshwater for a while (Lei et al., 2018). The results showed that intestinal damage of surviving zebrafish was severe, including cracking of villi and splitting of enterocytes. The abdomen of dead zebrafish was significantly swollen compared to the control. In another report, a large number of MPs were detected in water and fish (McNeish et al., 2018) from three major rivers tributaries of Lake Michigan, with the concentration at 3400–10000 particles/m^3. In addition, it should be noted that MPs are easily to absorb harmful substances from the surrounding environment and induce severe damage to aquatic animals (Ding et al., 2017), such as drugs, personal care products, and polybrominated diphenyl ethers (Blarer and Burkhardt-Holm, 2016;Wardrop et al., 2016).

However, the effects of MPs on freshwater organisms remain controversial. A study on daphnia in freshwater showed that although daphnia would consume more microplastic particles (Imhof et al., 2017), there were no significant effects on mortality, morphology, reproductive parameters and other processes. Moreover, in a study to evaluate the effect of MPs exposure on juveniles of planktivorous fish (Critchell and Hoogenboom, 2018), fish were fed with microplastic particles of the same size as natural food. Similarly, no obvious toxic effects were observed on the growth, physical condition, or behavior of fish. When tested with one-quarter food particle size MPs, up to 2102 particles of MPs can be detected in gastrointestinal tract of fish. It was reported that microplastic particles with less than 2 mm were more likely to be ingested by planktivorous fish (Critchell and Hoogenboom, 2018). Due to insufficient research on MPs pollution in freshwater, the adverse effects on freshwater organisms are not as clear as ocean environment. The toxic effects of MPs affect the survival of freshwater organisms and will continue to be the focus of future research.

3.4 Degradation of microplastic in the freshwater environment

Unfortunately, no bacteria that could degrade MPs have been found in freshwater environments. The possible reason is that research on freshwater started in recent years, and it still stays in exploration of the content, distribution, sources and other aspects of the freshwater environment. However, the degradation of MPs in freshwater is not without progress. It was found that biofilms cultured from freshwater environments can carry out carbon metabolism activities on PVC and PET substrates (Miao et al., 2021). Furthermore, the biofilm community attached to PVC was higher than PET. This research has great significance for the biodegradation of MPs in freshwater environments. Moreover, drinking water is closely related to our lives. Studies have pointed out that MPs have been detected in drinking water (Kosuth et al., 2018; Koelmans et al., 2019). It is not only a problem of environmental pollution but also related to our personal health. To ensure drinking water safety, some scholars put forward to combine ultraviolet advanced oxidation process with biological activated carbon in research on removing MPs in drinking water (Cui et al., 2019). The chemical bonds in MPs could be broken, and large MPs particles could be oxidized into small particles, which was more conducive to microbial transformation process. However, no experimental results have been reported, and further experiments are needed to verify the operation's feasibility. It is far from enough for the exploration of biodegradation of MPs in freshwater environments. In the future, it is well worth exploring more biodegradable bacteria and biofilms, and biodegradation of freshwater environments will become a research hotspot.

4 Microplastic pollution in the soil environment

Studies of microplastic pollution in soil environments have been reported in recent years. The presence, sources, and influence of MPs are as profound as investigations carried out in ocean (Wang et al., 2019). It was reported that the abundance of MPs will still exist in the coming years (Auta et al., 2017). Microplastic pollution in soil environment is still a critical problem and should be paid more attention to. Some strains could degrade MPs that were isolated from soil (Nowak et al., 2011; Sangale et al., 2019). These strains might play an important role in controlling microplastic pollution in the future.

4.1 Distribution and sources of microplastic in the soil environment

MPs are becoming widespread distributed in soil in recent years, which draws more attention from scientists (Rillig and Bonkowski, 2018). It was reported that MPs' contamination in soil might be a severe problem for the environment. The number of MPs discharged to soil is more than that in ocean environment each year. The concentration of MPs in soil environments maybe 4–23 times more than in the ocean environment (Nizzetto et al., 2016a). It was estimated that about 107000–730000 tons of MPs entered into arable lands annually in North America and Europe (Nizzetto et al., 2016b). It may also be reflected in countries with similar economic structures or plastic use as Europe and the Americas. In a survey of the Swiss floodplain, 90% of soil samples contained MPs (Scheurer and Bigalke, 2018), and PE particles accounted for 88% of all total MPs. Also, in Lake Dian and Lake riparian forest in Yunnan province in China, soil environment contained MPs with an average of 18760 particles/kg (Zhang and Liu, 2018).

MPs could enter terrestrial environment in various ways, such as sewage sludge, agricultural plastic mulch, illegal waste dumping, fertilizers (Horton et al., 2017; Bläsing and Amelung, 2018; Li et al., 2019). It was reported that processed sludge contained many MPs, and the application for soil fertilization could increase the abundance of MPs in soil environment (Corradini et al., 2019; Wang et al., 2019). The use of sewage sludge as soil fertilizer is widespread in many European and American countries (Nizzetto et al., 2016a), so this source alone may lead to a much higher plastic content in the soil than in ocean environment. During the last decades, the usage of single-use grocery bags and plastic mulch for agriculture has continued to increase (Wang et al., 2019), which leads to the contamination of PE film in cropland soil (Ramos et al., 2015). In addition to MPs detected in agricultural land, they can also be detected in the soil of nature reserves. However, the nature reserve is almost impossible to be polluted by sewage sludge, so floods and sandstorms are considered sources of pollutants in this area (Scheurer and Bigalke, 2018).

4.2 Separation and identification of microplastic in the soil environment

There is still no standardized analysis scheme for separating MPs in soil, mainly because soil is rich in various complex organic compounds (Bläsing and Amelung, 2018; Li et al., 2020c). It is difficult to completely distinguish organic compounds from MPs by conventional salt solution density separation, whether farmland soil, sludge or other stable soil structures (Li et al., 2020c). The salt solution used for density separation is not different from the separation of MPs in ocean environment. Therefore, the treatment of organic matter in soil becomes the key to detecting MPs in soil. H_2O_2 and Fenton reagent are still common reagents for the digestion of organic compounds. H_2O_2 at 70°C has a better effect on the digestion of organic compounds (Li et al., 2019). However, studies have found that H_2O_2 will reduce the extraction efficiency of MPs (Wang et al., 2018). NaOH and KOH are also used in digestion of organic matter in soil. Although they effectively remove organic matter from soil, these two reagents can cause MPs discoloration and degradation (Maes et al., 2017; Ruggero et al., 2020). A recent study used 98% H_2SO_4 to separate MPs from farmland soil to obtain pure polyethylene (Li et al., 2020c). This method can be widely used in agriculture.

Standard instruments used to detect MPs in ocean environments can also be used in soil. Although there are various separation reagents and testing instruments available, organic matter is an essential factor affecting MPs' detection in soil because organic matter can interfere with infrared recognition of MPs signal (He et al., 2018). Therefore, it is urgent to find an effective method for the detection of MPs in soil.

4.3 Effects of microplastic in the soil environment

Soil environment contaminated with MPs might cause serious damage to soil properties, protist communities, plants, and even agroecosystems (Li et al., 2020b). It was reported that bulk density, water holding capacity, soil fertility and stable water aggregates of soils could be affected by MPs contamination (de Souza Machado et al., 2018; Ma et al., 2018), and polyester fibers exhibited the most apparent effect. A case focused on soil protists (Rillig and Bonkowski, 2018) indicated that protists were likely to ingest micrometers of microplastic particles or even smaller particles. MPs could be transferred among soil organisms by soil protists, such as earthworms (Rillig et al., 2017). It was reported that MPs could induce damage to earthworms' tissues and immune systems (Rodriguez-Seijo et al., 2017). In a toxic effect investigation to wheat, low-density polyethylene and starch-based biodegradable plastic mulch film were selected as MPs residues (Qi et al., 2018). The result showed that the whole growth process of wheat could be affected by MPs residue, and biodegradable plastic mulch exhibit more severe toxic effects than that of PE. Specifically, vegetative and reproductive of wheat were inhibited. Plant height, number of fruits, and root biomass of wheat were also significantly reduced. MPs also showed high adsorption capacity for heavy metals and antibiotics (Li and Zhang, 2018; Li et al., 2020b) in soil environments. Polyamide particles could even serve as a carrier for antibiotics. MPs, which absorbed heavy metals and antibiotics, could directly affect the survival of microbes. MPs posed a significant threat to soil environments and affected the growth of soil organisms and plants. However, the level of MPs pollution, subsequent effects on community, and action mechanisms are still unclear (Li et al., 2020b). Hence, investigations of MPs in soil are still a research hotspot, attracting extensive attention from scientists.

4.4 Strains of biodegradable microplastic found in the soil environment

Although there are biodegradable plastics now, the degradation of MPs in the environment is still of great importance. As in ocean environment, microplastic pollution in soil can also be treated and biodegraded by microbial. Biodegradation is considered the most commonly accepted, effective, and eco-friendly method (Shah et al., 2008). In addition to active strains found in seawater, some strains were isolated and identified from soil (Table 2). Strains isolated in soil were mainly aimed at the degradation of PE and PP.

An elite PE deteriorating fungi, *Aspergillus terreus strain MANGF1*, was isolated from Avicennia marina's rhizosphere soil (Sangale et al., 2019). This *aspergillus terreus* strain was reported to be a highly efficient and elite polythene deteriorating fungi, and it can reduce more than 50% MPs at pH 9.5. It was reported that many strains with the ability to degrade PE were found in waste coal, forest, a crater in Poland (Nowak et al., 2011), such as *Bacillus mycoides*, *Acinetobacter baumannii*, *Pseudomonas fluorescens*, and *Staphylococcus cohnii*. The dominant microorganisms in waste coal and crater soil were bacteria, and fungi in forest soils were detected as filamentous fungi. These strains resulted in a weight loss of 0.13% to 17.03% of the modified PE film within 225 days. It provided more options for the degradation of PE in the environment. Also, two strains (*Bacillus-27, Rhodococcus-36*) that could degrade PP were found in mangrove sediments (Auta et al., 2018). After processing with the two strains, the structure and morphology of PP changed obviously by using FTIR and SEM analyses. After 40 days of incubation experiment, the weight loss was 4.0% by *Bacillus-27* and 6.4% by *Rhodococcus-36*. The results showed that the isolated strains exhibited the ability to degrade PP. By contrast, the degradation rate of soil degradation strains was slightly higher than that of ocean environment. Gravimetric weight loss can be as high as 50%. However, it can be observed that microbial degradation rate was not stable during different experiments. That is probably because the biodegradation rate of plastics was related to environmental conditions, strain types, and the state of microbes that live in them (Nowak et al., 2011). It is undeniable that UV photodegradation also significant affects MPs and contributes to Raman spectroscopy analysis (Lenz et al., 2015; Welden and Cowie, 2017). The combination of photodegradation and biodegradation may be considered to help remove environmental MPs.

Table 2 List of microplastic degrading microbial strains from soil environment

Type of Strains	Name of Strains	Type of MPs	Action time (d)	Gravimetric weight loss (%)	Reference
Fungi	*Aspergillus terreus MANGF1*	PE	60	50.00±4 (pH9.5)	Sangale et al., 2019
Bacteria	*Bacillus-27*	PP	40	4.0	Auta et al., 2018
	Rhodococcus-36	PP	40	6.4	Auta et al., 2018
	Bacillus subtilis-MZA-75	PUR (polyurethane)	28	–	Shah et al., 2013
	Paenibacillus amylolyticus TB-13	PLA(Poly(lactic acid))	14	–	Teeraphatpornchai et al., 2003
	Bacillus sp. and Paenibacillus sp.	PE	30	14.7	Park and Kim, 2019
	Bacillus cereus, Bacillus pumilus and *Arthrobacter*	HDPE, LDPE	14	22.41, 21.70	Satlewal et al., 2008
	Rhodococcus ruber	PE	30	8	Orr et al., 2004
	Bacillus mycoides, Acinetobacter baumannii, Pseudomonas fluorescens, Staphylococcus cohnii and Staphylococcus xylosus	LDPE	225	0.13–17.03	Nowak et al., 2011
	Achromobacter xylosoxidans	HDPE	44	9	Kowalczyk et al., 2017
	Rhodococcus ruber	PS	56	0.8	Mor and Sivan, 2008
	Ideonella sakaiensis 201-F6	PET	42	–	Yoshida et al., 2016
	Hyperthermophilic	PS	56	7.3	Chen et al., 2020
	Chelatococcus-E1	PE	80	–	Jeon and Kim, 2013

5 Conclusions and outlook

Today, MPs have become a major class of pollutants and are distributed in oceans, freshwater and soil. In summary, current knowledge of MPs sources and distribution, toxic effects, identification, and biodegradation is described here. MPs are most detected and identified in water, soil, edible salt, and even food. It brings severe toxic effects to the environment and might bring adverse effects to animals and human beings via food chains. Although the toxic effects of MPs were investigated, the mechanism of MPs is still not clear. Besides, research studies focused on MPs detection and identification based on their particle size and chemical bonds are also described in this work. MPs particles are long-lived pollutants that are highly resistant to environmental degradation. Therefore, the investigation and application of biodegradation of MPs with different microbes are summarized and discussed. This work will contribute to a better understanding of MPs pollution in the environment and MPs identification, toxicity, and biodegradation, which may help assess and control MPs exposure. To strengthen monitoring and analysis of environmental MPs, the following aspects need to be addressed soon:

1) To explore the biotoxicological effects of MPs and strengthen research on the mechanism of toxicity.

2) The actual level of contamination of MPs in terrestrial environment is not yet known, and a rapid, sensitive and accurate method is needed to analyze the migration and fate of MPs in soil environment.

3) Novel and highly active microbes, including bacterial and fungi, which can degrade MPs, are current trends.

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