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Environmental behaviors and degradation methods of microplastics in different environmental media

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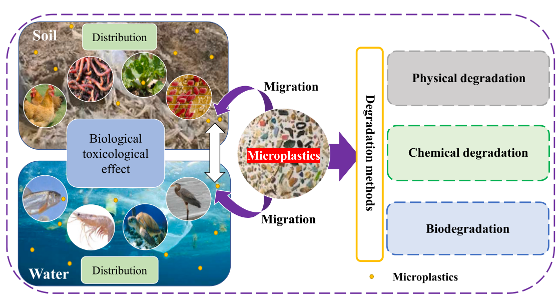
HIGHLIGHTS

- Estuarine sediments and agricultural soils show high concentration of microplastic.
- The effect of microplastic on organisms mainly depends on its concentration and size.
- Food chains and rivers are important pathways for microplastic migration.
- Photodegradation is the most commonly used method for microplastic degradation.
- Suggestions and futures perspectives are proposed.

GRAPHICAL ABSTRACT



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ABSTRACT

Microplastics, as a group of emerging contaminants, are widely present in environmental media and have the potential to endanger the ecological environment and human health. Due to the inconsistencies and difficulties inherent in the analysis of microplastic particles, global monitoring data on the distribution of microplastics in the environment are still far from sufficient. The fate and migration of microplastics in the environment are also uncertain. Therefore, there have been increasing reviews on the distribution, biological effects, migration, and health risks of microplastics. However, reports focusing on the degradation of microplastics are still rare. Understanding and commanding the environmental behavior of microplastics are of great significance to explore the treatment of microplastic pollution. Although some preliminary studies on microplastics have been carried out, there is still an urgent need to conduct a comprehensive study on environmental behaviors and degradation methods of microplastics in different environmental media. This article summarizes the recent advances on microplastics, basically includes the distribution and ecological impact of microplastics in soil and water environments, then elaborates the migration behavior and influencing factors of microplastics, and focuses on the research progress of microplastics degradation methods. On this basis, the problems existing in the current

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research and the future development directions have been proposed. This review could provide a more systematic reference for the development and research of microplastics in the future.

1. Introduction

In recent years, with the increasing use of plastic products worldwide, the problem of plastic waste pollution in the environment has become increasingly severe (Ceccarini et al., 2018). It is reported that the global plastic output in 2016 was 335 million tons (Ceccarini et al., 2018), while the latest data show that the output in 2020 has reached 367 million tons (Tiseo, 2021). And the high consumption of plastics is accompanied by a large amount of plastic waste, of which only 6%–26% is recycled (Alimi et al., 2018). Compared with general plastics, microplastic has the characteristics of high abundance and long transmission distance (Zhou et al., 2020a). It is more easily to release harmful substances in the environment and absorb toxic substances (such as polychlorinated biphenyls and polybrominated diphenyl ethers, etc.) than ordinary plastics. Because it is similar in size to low-end organisms in the food chain, its surface can attach microorganisms and other organisms. Therefore, the flow of microplastic along the food chain may cause the spread of invasive species and pathogenic microorganisms (Carbery et al., 2018). Microplastic is also easy to be absorbed by organisms with different nutritional levels (Browne et al., 2011), and it has been detected in some organisms in different environments (de Souza Machado et al., 2018; Rochman, 2018). The ingested microplastics can cause different degrees of damage to the digestive tract of organisms and affect the reproduction rate and enzyme activity of some organisms. The microplastics in the environment can also affect the composition of the biological community and nitrogen cycle (Chae and An, 2017). With the expansion of microplastic pollution scope in the environment, its hazards in the environment cannot be ignored (Ivar do Sul and Costa, 2014).

To better understand the impact of microplastics on the natural environment and human health, a lot of studies have been carried out on microplastics (Ge et al., 2021; Guo et al., 2020; Hasan Anik et al., 2021; Koutnik et al., 2021; Liu et al., 2021a; Ragusa et al., 2021; Ren et al., 2021; Sharma et al., 2020; Shi et al., 2021; Yang et al., 2021; Zhou et al., 2020b). For example, the sources, migration, and toxicology of microplastics in the environment have been reviewed by Guo et al. (2020). The distribution and risk assessment of microplastics in the environment have also been reported (Zhou et al., 2020b). However, most studies only focus on the sources, distribution, toxicity, and risk assessment of microplastics in a single environmental medium (Ge et al., 2021; Hasan Anik et al., 2021; Koutnik et al., 2021; Yang et al., 2021), while there are relatively few studies on the degradation methods and migration of microplastics (Ren et al., 2021; Sharma et al., 2020). At present, the relevant treatment technologies and degradation methods of microplastics mainly include coagulation, precipitation, sand filtration, membrane separation technology, electrocoagulation, pyrolysis, and so on (Hashmi, 2021; Shen et al., 2020). Microplastics can accumulate and migrate in animals and plants, which results in a negative impact on animals and plants (Liu et al., 2021a). At the same time, inhalation or ingestion of microplastics can change the microbial structure in the human lungs and gastrointestinal tract (Shi et al., 2021). Current reports have found that there are different types of microplastics in different waters and soils, and their sources and distribution are related to human activities (Koutnik et al., 2021). Recently, microplastics have also been found in the human baby placenta (Ragusa et al., 2021). Therefore, microplastics in the environment have become a research hotspot in recent years. Results searched through Web of Science and MEDLINE® manifest that the number of publications has been increasing exponentially in the past 4 years (Fig. 1). In 2020, more than 1881 papers related to microplastics were published on the Web of Science.

Understanding and commanding the environmental behavior of microplastics are of great significance to explore the treatment of microplastic pollution, it is necessary to comprehensively summarize the distribution, influence, migration, and degradation methods of microplastics in different environmental media. Therefore, the objectives of this review are to (1) introduce the distribution of different types of microplastics in water and soil; (2) clarify the impact of microplastics on organisms in the environment; (3) explore the migration behavior of

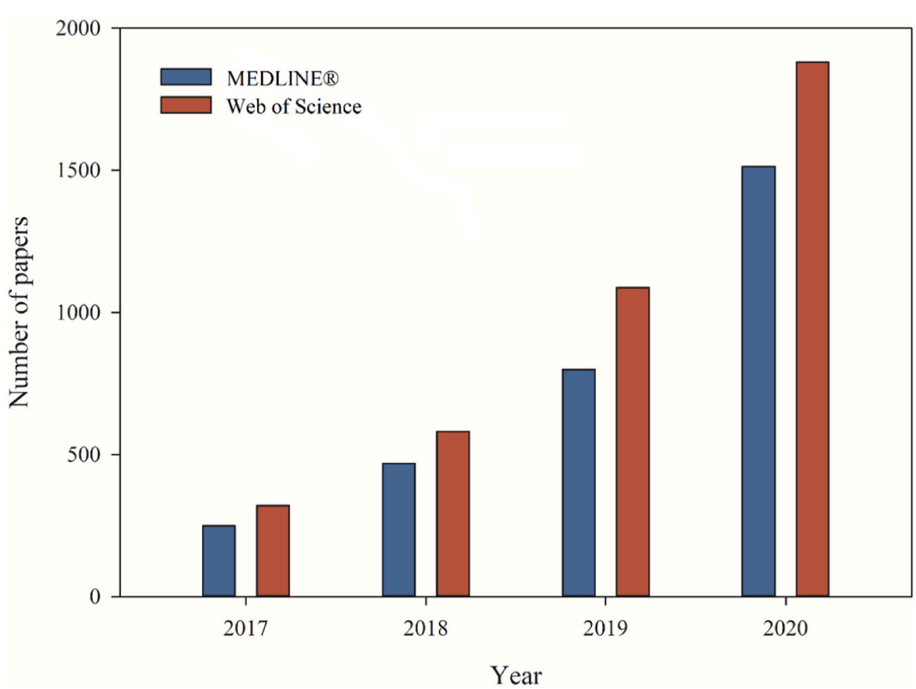

Fig. 1. Trend diagram of microplastics-related literature from 2017 to 2020.

microplastics in water and soil; (4) summarize the three types of degradation methods of microplastics; and (5) propose the knowledge gaps in the current microplastics research, and put forward corresponding suggestions for follow-up research.

2. Distribution of microplastics in the environmental media

2.1. Distribution of microplastics in soil

Microplastics are widely distributed in terrestrial soil. Compared with the marine environment, the annual amount of anthropogenic plastics discharged into the land is about 4–23 times higher than that of the ocean (de Souza Machado et al., 2018). These large plastic fragments that flow into the environment are eventually broken down into secondary microplastics (Lechthaler et al., 2020). Possible sources of soil microplastics are mainly open waste dumping, incineration, road waste, tire wear, landfills, construction, sludge from sewage plants, and agricultural plastic applications (Waldschlager et al., 2020). Most microplastics enter the soil through recreational activities, wastewater irrigation, sludge landfills, and surface runoff, and a few enter the soil through animal excretion or external forces (such as rain and wind) (Waldschlager et al., 2020). Ding et al. found multiple different types of microplastics in Shaanxi agricultural soils, with concentrations ranging from 1430 to 3410 particles kg^{-1} (Ding et al., 2020b). Another study showed that the average abundance of microplastics in the cultivated soil of the Yunnan Plateau was 9.8×10^3 particles kg^{-1} (Huang et al., 2021a). These data indicate that there are already high concentrations of microplastic pollution in agricultural cultivated soil. It is also found that the content of microplastics in soil is highly correlated with the amount of sludge-based fertilizer, indicating that the input of sludge-based fertilizer can increase the abundance and content of microplastics in soil (Zhang et al., 2020a). And there is a highly significant linear correlation between the number of plastic films and the number of plastic residues in soil, indicating that plastic film mulching may be the main source of microplastics in soil (Huang et al., 2020). The concentration of microplastic particles was 1075.6 ± 346.8 pieces kg^{-1} in soil in which the film was used continuously for 24 years. This shows that the plastic cover is an important source of macroscopic and microscopic plastic pollution in the soil media (Huang et al., 2020). Different field conditions and levels of bulk plastic fragmentation can affect the distribution and abundance of microplastics, and microplastics can be dispersed and transported by surface runoff and/or infiltration (Kim et al., 2021; Lechthaler et al., 2020). Therefore, agricultural and urban soils can be considered important sources and sinks of global microplastic pollution.

Microplastics are not only found in cultivated soils. Researchers have found traces of microplastics in soils, wetlands, and sediments all over the world. Fig. 2 shows the distribution of different types of microplastics in different soils and sediments. It can be seen that in the several soils and sediments investigated, except for polypropylene (PP) is mainly distributed in wetland soil, the microplastics in other soils and sediments are mainly polyethylene (PE). But it is not difficult to see that there are more PP and PE microplastics in all the soils and sediments studied, because these two polymers are the most commonly used types of plastics. The distribution of microplastics in soils and sediments shows obvious regional differences, and the distribution and concentration of microplastics in different research areas are different. In the future, it is necessary to further study the correlation between the distribution, abundance, and type of microplastics in different regions to provide systematic reference information for pollution control.

2.2. Distribution of microplastics in the water environment

Microplastics are now ubiquitous in marine and freshwater systems (Wu et al., 2019). Studies of microplastic pollution in freshwater systems

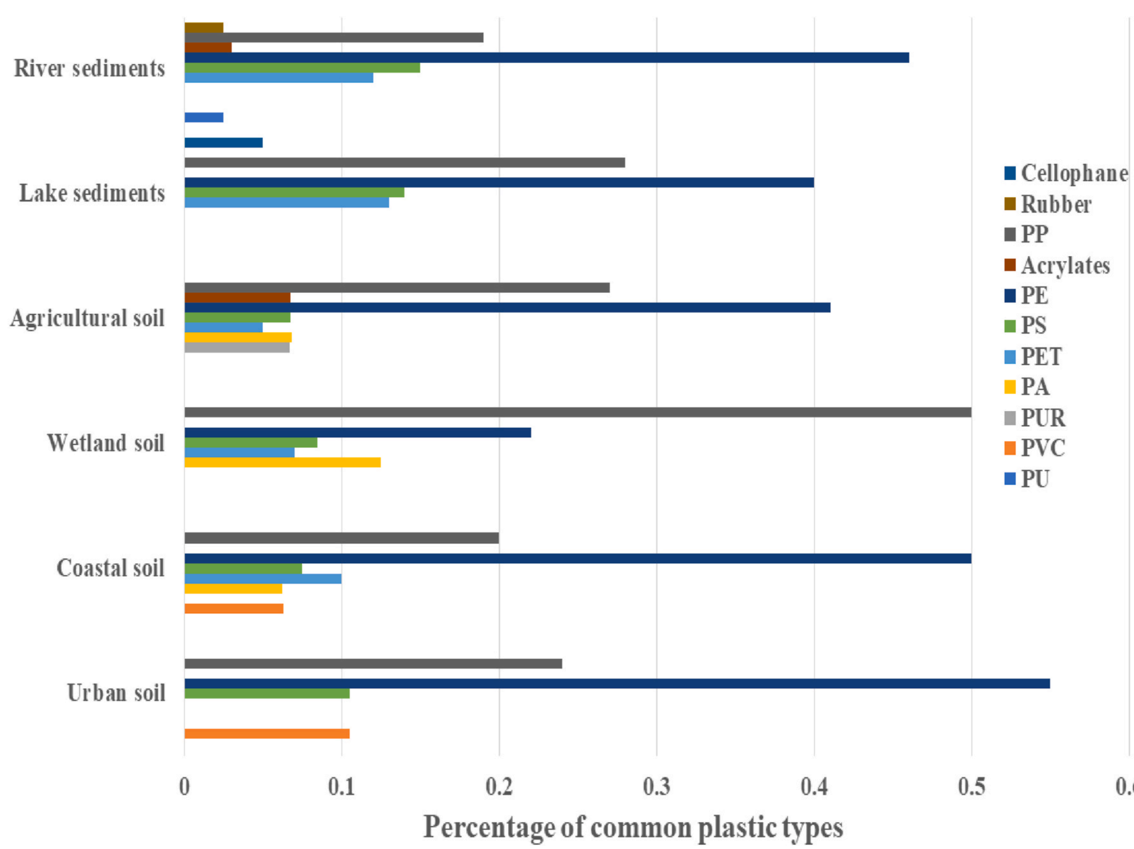

Fig. 2. The distribution of common plastic polymer types in soil and sediments, according to the analysis of 136 articles (Koutnik et al., 2021). (Notes: PVC: polyvinyl chloride; PA: polyamide; PE: polyethylene; PS: polystyrene; PP: polypropylene; PU: polyurethane; PET: polyethylene terephthalate; PUR: polyurethane rubber.)

(such as rivers, lakes, estuaries, etc.) are important because they provide information on the flow of microplastics from continental water environments to the ocean (Ziajahromi et al., 2017). Urban sewage treatment plants, fisheries, ports, shipping, septic systems, tourism, and landfills are the main sources of microplastics in the water environment (Hasan Anik et al., 2021). Direct discharge of wastewater, carryover by surface runoff, scouring by rainwater, transportation by lakes and rivers, and the impact of human activities are the main ways for microplastics to enter the water environment (Waldschlager et al., 2020). The average abundance of microplastics found in Rawal Lake surface water and sediments was 1.42 items L^{-1} and 104 items kg^{-1}, respectively (Irfan et al., 2020). Surprisingly, microplastics are also present in groundwater systems, possibly from septic tanks and municipal sewage systems (Ren et al., 2021). A report on the Antuã River in Portugal found that the abundance of microplastic in water was 58–193 particles m^{-3} in March and 71–1265 particles m^{-3} in October. This indicates that the abundance of microplastic in water is affected by seasonal changes and human activities (Rodrigues et al., 2018). Liu et al. found that the abundance of microplastic in river sediments was very high (4980 $\pm$ 2462 items kg^{-1} dry weight), and the main component was PE, with an average content of 49.3% (Liu et al., 2021b). It has also been reported that the abundance of microplastic in estuarine sediments was 20–7900 items kg^{-1} (Jiang et al., 2021). Moreover, microplastics have been found in the surface and deep seawaters, in the oceans and coastlines from the two poles to the equator (Erni-Cassola et al., 2017), and in the oceans from remote coastlines to densely populated coastlines (Dekiff et al., 2014). It is reported that the distribution of microplastics in coastal waters such as the northeastern Pacific Ocean, Vancouver Island on the west coast, Queen Charlotte Strait, and the Strait of Georgia. It is found that the concentration of microplastic near the coast is 4–27 times that of the coastal northeastern Pacific Ocean, and the concentration of microplastic ranges from 8 to 9200 particles m^{-3}. The abundance of microplastic on the sea surface was 0.13–545 items m^{-3} (Jiang et al., 2021), indicating that deep-sea areas, sea canyons, and coastal shallow waters may be the accumulation place of microplastic. By studying the distribution of microplastic in the Gorgan Bay area, Bagheri et al. found that fibers generally existed in organisms and sediments in the bay, with a content of about 42.4% and the abundance range from 80 $\pm$ 25 to 740 $\pm$ 105 particles kg^{-1} (Bagheri et al., 2020). This indicates that the partially aggregated microplastic may eventually enter organisms and sediments. In addition, microplastics were widely detected in fish, mollusks, zooplankton, mammals, and birds, indicating that microplastics were also distributed within aquatic animal populations (Fu et al., 2020). Clearly, in contrast, estuarine sediments and nearshores have arisen high levels of microplastic pollution (Ghayebzadeh et al., 2021).

Since microplastics flow into the ocean from estuaries, and the estuarine system is the boundary between freshwater and marine environments, rivers can be considered as one of the sources of marine microplastics, while estuarine sediments and oceans may be the sinks of rivers (Waldschlager et al., 2020). The abundance of microplastics in water is affected by seasonal changes and human activities. Compared with the dry season, a higher abundance of microplastic is found in the rainy season, indicating that the prevention and control of microplastics should be carried out before the rainy season (Jiang et al., 2021; Rodrigues et al., 2018). Fig. 3 shows the distribution of different types of microplastics in different water environments. It can be seen from Fig. 3 that PE is mainly distributed in rivers, lakes, and surface water, polystyrene (PS) is mainly distributed in groundwater and urban canals, and PP is the most common polymer in all water samples. Although PE is the most produced and used polymer, it is not the most common in all water samples. Surprisingly, few studies have detected polyvinyl chloride

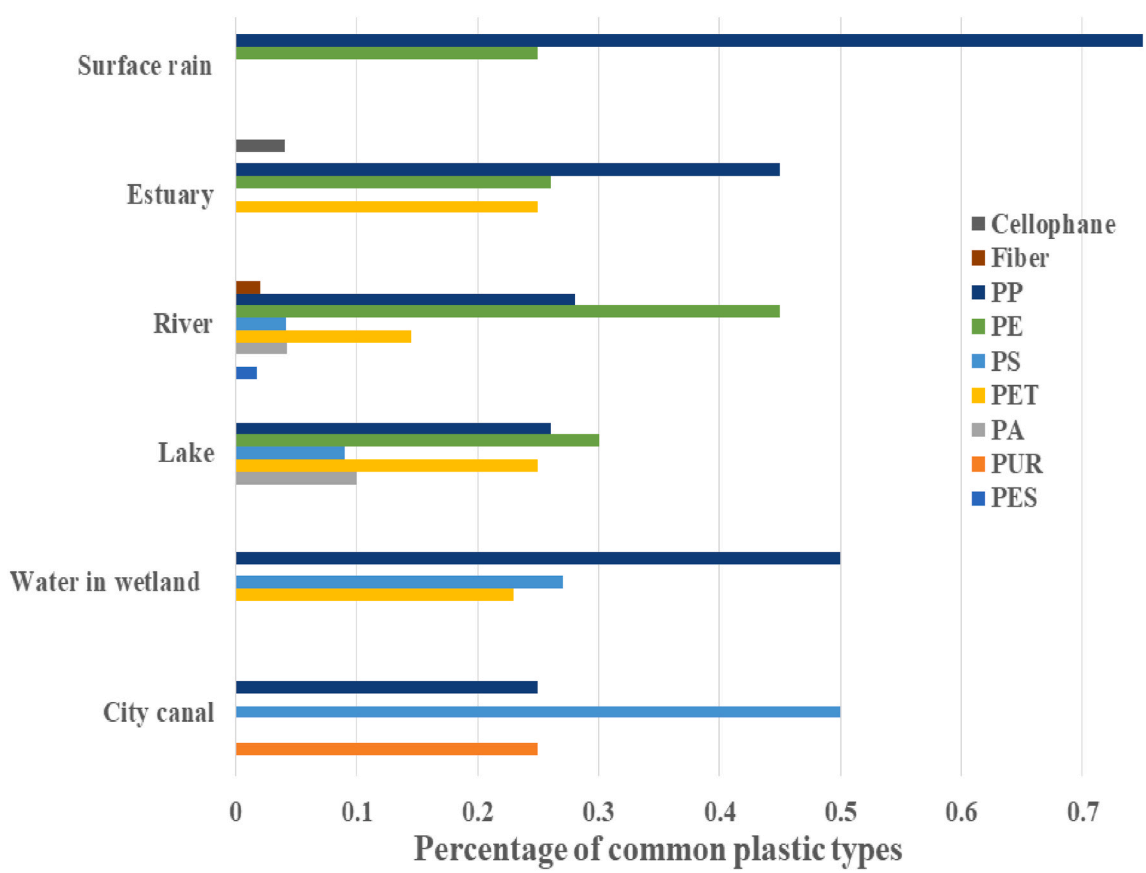

Fig. 3. The distribution of common plastic polymer types in the water environment, according to the analysis of 136 articles (Koutnik et al., 2021). (Notes: PA: polyamide; PE: polyethylene; PS: polystyrene; PP: polypropylene; PET: polyethylene terephthalate; PES: polyethersulfone; PUR: polyurethane rubber.)

(PVC) in water, which maybe because it is rarely used in the disposable packaging industry. Due to polyethylene terephthalate (PET) being often used in the packaging industry, it is also detected in water samples. In the future, the monitoring of microplastics in the water environment should be strengthened, and the impact of microplastics on the environment should be assessed more scientifically, especially the impact of microplastics on aquatic ecology and human health.

3. The impact of microplastics on organisms in the environment

The pollution caused by microplastics in water and soil environmental media has attracted increasing attention from all walks of life. According to reports, microplastics are easily swallowed by organisms in the environment, and then enter the digestive tract of organisms, then produce toxic effects on these organisms (Zhang et al., 2020c). Through the enrichment of the food chain, microplastics may eventually be ingested by humans and enter the body, thereby causing possible harm to human health. Existing research results are based on the use of known types of microplastics to conduct control experiments. *Table S1* summarizes the impact of microplastics on organisms in the environment, including soil organisms, aquatic organisms, and humans.

3.1. The impact of microplastics on soil organisms

Microplastic affects the physicochemical properties of the soil. In addition, through studies on soil animals such as earthworms, nematodes, and springtails, it has been shown that soil animals could ingest microplastics, and the ingested microplastics can harm the growth, development, and reproduction of animals in the soil environment (Zurier and Goddard, 2021). For plants, microplastics can damage their photosynthesis by inhibiting plant growth, reproduction, and protein synthesis in their bodies, exerting a negative impact on plant growth and development (Khalid et al., 2020). Microplastics even have a certain inhibitory effect on the production and transformation of energy in the soil microorganisms as well as the synthesis and utilization of proteins, which changes the composition of the soil root microbial community and affects the activities of various enzymes, eventually destroying the beneficial plants-microbes interaction system, etc. (Jacques and Prosser, 2021) (Fig. 4).

3.1.1. The impact of microplastics on soil animals

Microplastics can affect the growth and reproduction of soil animals (Zurier and Goddard, 2021). Presently, the research on the toxicity of microplastics to soil invertebrates mainly focuses on earthworms and springtails (Zhu et al., 2018b). Previous studies have shown that after soil animals ingest microplastics for a while, microplastics can change the intestinal microbial community of animals and reduce their bacterial diversity (Ju et al., 2019; Zhu et al., 2018a). These animals can also experience symptoms such as decreased enzyme activity, reproductive rate, growth retardation, and increased mortality (Jiang et al., 2020). For example, Huerta et al. put the earthworms (Oligochaeta, lumbrical) in dry bulk soil with a range of 0.2%–1.2% concentration of PE for 60 d. The experiment showed the mortality of earthworms increased, their growth and reproduction rate decreased significantly (Boots et al., 2019). The reproductive rate, body length, and survival rate of nematodes also showed a significant inhibitory effect. Ding et al. showed that microplastics can reduce the weight and reproduction of soil worms, and when the concentration of microplastics in soil was higher than 0.024%, the survival rate of worms was significantly reduced (Ding et al., 2020a). These changes indicate that microplastics have obvious toxic effects on soil animals (Wang et al., 2021a, 2021c). However, the impact of microplastics on soil animals is not only because microplastics are ingested in the body, but also because they change the surrounding environment (Zhang et al., 2019) or cause physical damage to organisms

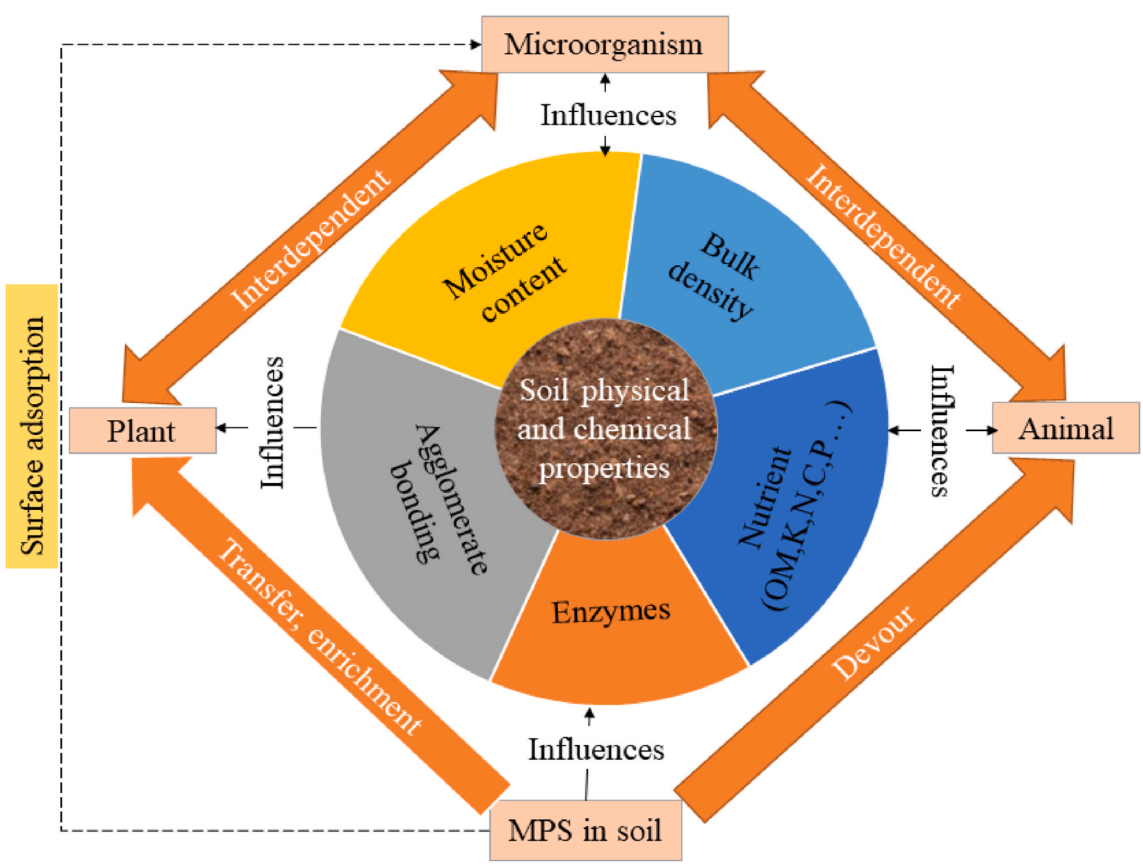

Fig. 4. Interactions of microplastics with soil organisms and soil physicochemical properties.

through internal wear and blockage (Huerta Lwanga et al., 2016).

However, the concentration of microplastics used in existing research is very high, and the research results obtained may not apply to the actual environment. The biological toxicity exhibited by microplastics is highly correlated with their concentration. High concentrations of microplastics are more toxic to organisms. Although some achievements have been made in the research on the impact of microplastics on soil animals, the toxicity experimental results were not necessarily comparative due to their differences in body shape, habitat time, lifestyle, and other aspects, as well as the uneven distribution of animals in soil. Therefore, more in-depth research on soil animal communities is needed to supplement the existing database.

3.1.2. The impact of microplastics on plants

Microplastics also affect the growth of terrestrial plants (Zurier and Goddard, 2021). At present, most of the effects of microplastics on soil plants are concentrated on the soil-plant system. Land plants provide a landing point for microplastics in air. As time goes on, microplastics can damage the photosynthesis of leaves. The microplastics falling on the surface of leaves can also be absorbed by plants, thereby inhibiting protein synthesis in plants and affecting oxidative stress response (Bi et al., 2020). Different types and concentrations of microplastics can affect crop growth (Boots et al., 2019). Boots et al. found that adding synthetic fibers, high-density polyethylene (HDPE) and polylactic acid (PLA) microplastics to the soil could inhibit the growth and reproduction of plants. When ryegrass seeds were exposed to synthetic fibers and biodegradable PLA, the germination rate of ryegrass seeds was low. In this test, PLA reduced the stem height of ryegrass and shortened the length of violet branches; the biomass of ryegrass exposed to HDPE was significantly reduced compared with the control group (Boots et al., 2019). It is worth noting that these effects are all observed in experiments with high concentrations of microplastics. Microplastics in different sizes have different effects on plants (Jiang et al., 2019; Tang et al., 2020). The toxic effect of microplastics on plants increases with the decrease of their particles (Tang et al., 2020). The key for microplastics to enter the food chain through plants is plant absorption and transmission (Liu et al., 2021a). Studies have shown that 100 nm PS microplastics can enter the root system of higher plant broad bean, which blocks the cell wall stomata and connections between cells, thereby affecting nutrient transmission. At the same time, it is observed that 100 nm microplastics at a concentration of 100 mg L^{-1} have a significant inhibitory effect on the growth of higher plant broad bean, and the genetic toxicity caused by 100 nm microplastics was stronger than that of 5 μm microplastics (Jiang et al., 2019).

The above researches show that plants can absorb and transmit soil microplastics, which damage plant photosynthesis, inhibit plant growth, reproduction, and protein synthesis inside, hinder the absorption of water and nutrients by plant roots as well as significantly change plant roots traits and plant biomass. It illustrates that microplastics themselves have certain toxic effects on soil plants. The current research results are only limited to the analysis of a few species. Different types, concentrations, and sizes of microplastics have different effects on plants (Boots et al., 2019; Jiang et al., 2019). The concentrations of microplastics in the experiments mostly are higher than that of the real environment. Such condition is conducive to the accumulation of microplastics in plants, but it is different from the real growth environment of plants. Therefore, that is a key limiting factor that needs to be considered in future research.

3.1.3. The impact of microplastics on soil microorganisms

Compared with the soil without microplastics, adding plastic fibers and HDPE or PLA to the soil could significantly reduce the micro-aggregates in soil (Boots et al., 2019). Meanwhile, microplastics can provide adsorption sites for microbes, so that microbes can live on the surface of microplastics for a long time and form biofilms. Microbial communities are formed on microplastic fragments that are significantly different from the soil, which may change the functional properties of soil (Sander, 2019). Microplastics are easy to accumulate bacteria such as *Pseudoalteromonas*, *Vibrio*, and *Alteromonas*, which play an important role in carbon metabolism (Sun et al., 2020). The bacteria on their surface have higher biological toxicity after accumulation, and they are likely to cause body infections after entering the body, and the presence of biofilm may cause microplastics to adsorb more pollutants (Sun et al., 2020). The difference of microplastics in morphology and surface structure can cause differences in the composition of the surface biofilm and the structure of the microbial community. Yang et al. added high-concentration microplastics to the soil during the experiment. After 30 d of incubation, it was found that the respiration of microorganisms in soil has changed significantly. The addition of microplastics stimulated the activities of β-glucosidase, urease, and phosphatase in soil, and their activities decreased with the increase of microplastics content (Yang et al., 2018). Polyamide 66 microplastic can inhibit the metabolism and transport of amino acids. This result suggests that polyamide 66 microplastic has a certain inhibitory effect on the production and transformation of energy, synthesis, and utilization of proteins, as well as cell growth in microorganisms (Zhao et al., 2020).

To sum up, microplastics can provide adsorption sites for microorganisms as a carrier for microorganisms. Microplastics allow microorganisms to exist on their surfaces for some time and form biofilms, which have a certain inhibitory effect on respiration, energy production, and transformation, as well as the protein synthesis and utilization of microorganisms. It can affect the composition of the soil root microbial community and the activities of multiple enzymes, destroying the beneficial plant-microbe interaction system (Xu et al., 2019). Currently, the research on the influence of microplastics on soil microorganisms is still limited. How to apply the existing microbial testing methods to the microbial communities attached to the surface of soil microplastics, revealing that the influence mechanism of microplastics on soil microorganisms is the focus of research on soil microorganisms in the future.

3.2. The impact of microplastics on aquatic organisms

The widespread of microplastics in aquatic ecosystems has made people pay more and more attention to the potential impact of microplastics on aquatic biota (Di and Wang, 2018). Due to their relatively stable nature, microplastics can exist in the environment for long periods and be often mistakenly eaten by plankton (Cole et al., 2015) (such as copepods, red snappers, juvenile fish, salmon, and jellyfish), filter-feeding organisms, vertebrates (such as fish, seabirds and marine mammals), etc. (Miao et al., 2020). But the ingestion of microplastics can cause damage to aquatic organisms (Ali et al., 2016). For example, microplastics cannot be digested nor easily expelled from the body, which accumulates in the digestive tract of aquatic organisms for the long term, so that the organisms have a sense of satiety leading to malnutrition and even death due to the inability to feed. The inherent chemical toxicity and compound pollutants of microplastics may cause direct harm to the ingested organisms and be accumulated in the organisms at various levels through the food chain (Bouwmeester et al., 2015), leading to a series of toxicological effects in the organisms (Zhang et al., 2020c). Various aquatic organisms in the world have been found to ingest microplastics (Cole et al., 2013). Microplastics are often detected in the body of aquatic organisms such as shellfish, fish, seabirds, etc. (Avio et al., 2017). The microplastics detected in aquatic organisms mainly include fibers (Fu et al., 2020). It is estimated that more than 267 species are affected by the ingestion of microplastics in the world, including most species of sea turtles and almost 50% of species of seabirds and marine mammals (Desforges et al., 2014). For example, the ingestion of microplastics by sea turtles can block the digestive tract or bladder of sea turtles, leading to their death (Ryan et al., 2016). The tubifex worms, which survive in the transfer of high concentrations of plastic additives and desorption pollutants, are a food source for many large invertebrates. For instance, leeches and small insectivorous fish are also eaten by salmon and trout (Hurley et al., 2017). The resistance to food can lead to the hunger and death of organisms and high-level predators in the food chain in the aquatic system (Kang et al., 2019), thus posing a threat to the safety of the ecological environment.

Previous studies have shown that ingested microplastics harm most aquatic organisms. As an illustration, the inherent chemical toxicity and the compound pollutants of microplastics may also cause direct damage to aquatic organisms. Due to the predation of the food chain, microplastics may accumulate in all levels of organisms throughout the food chain, causing the decline of spawning capacity and germ cell quality. However, the specific mechanism of microplastics in aquatic organisms still needs to be further explored.

3.3. The impact of microplastics on human health

As shown in *Fig. S1*, humans can breathe in microfibers that float in air. It is known that air particles can reside deep in the lungs of humans (Wright and Kelly, 2017), causing various diseases including cancer (Zhang et al., 2020b). Through the study of breathing simulation experiments on different types of commonly used masks, it is found that people wearing masks increase the risk of inhalation of microplastics (Li et al., 2021b). According to survey statistics, humans ingest approximately 0.1–5 g of microplastics per week (Senathirajah et al., 2021). Studies have indicated that salt, honey, daily drinking beer, and drinking water also contain microplastics (Fadare et al., 2021). Through these consumer products, humans may ingest more than 5800 synthetic debris particles each year, of which tap water (88%) contributes the most (Kosuth et al., 2018). Food chain enrichment transmission is an important way for microplastics exposure (*Fig. S1*). The absorption and accumulation of microplastics by eating contaminated fish, poultry, and crustaceans indicate that microplastics may be passed into the food chain through animals (Abbasi et al., 2018; Daniel et al., 2021). In addition, the abundance of microplastics in the feces of animals and humans indirectly proves the fact that microplastics have been transmitted in the food chain (Schwabl et al., 2019). Due to ethical reasons, the risks of microplastics and human health can be enlightened by the results of mouse experiments and in vitro experiments. Studies have shown that microplastics can reduce the diversity of communities in the intestines of mice, aggravate liver metabolic disorders, and cause intestinal inflammation, as well as neurotoxicity and cytotoxicity (Deng et al., 2017; Reineke et al., 2013; Zheng et al., 2021). Microplastics and their adsorbed pollutants may pose a threat to human health (Rist et al., 2018). Recent studies have found that there were also microplastics in the placenta of human babies, the microplastics in the placenta can penetrate deeply into tissues through several unclear active and passive transport mechanisms (Ragusa et al., 2021). This shows that the threat of microplastics to human health cannot be ignored. However, the specific ways in which microplastics enter the placenta need to be further explored.

In brief, there is no consensus on the impact of microplastics on human health, and the research in this field is still in its infancy. There is still a lack of relevant research on the assessment of microplastics exposure as well as the correlation between microplastics and human health (Shi et al., 2021). In the future, it is necessary to further establish and strengthen the detection and evaluation system of microplastics in the environment. Researches on the effect of microplastics on human health still need to be further carried out, especially more data on the toxic effects of microplastics on human health should be continuously improved.

4. Migration of microplastics in the environment

4.1. Migration of microplastics in the soil environment

As shown in Fig. 5, due to long-term weathering, mechanical abrasion, ultraviolet radiation, and their interaction with other components in soil, the plastic entering the soil can be decomposed into smaller microplastics or even nanoplastics, making it easier to migrate in soil (Li et al., 2020b). Microplastic can migrate horizontally and vertically in soil. Its migration process in the soil environment is affected by the external natural climate (wind and rain) (Ji et al., 2021), soil flora and fauna, human activities (Zhu et al., 2018b), the characteristics of the microplastics themselves (size, density, and shape) (Blasing and Amelung, 2018), other external forces (mechanical disturbance) (Ding et al., 2021), and other factors. The low Fe/Al oxide content in soil and high pH can increase the migration ability of microplastics (Wu et al., 2020). The effect of wind can cause long-distance horizontal migration of microplastics, and rainfalls affect the vertical migration of microplastics in soil (Ji et al., 2021). At present, there are many studies on the migration of microplastics in the soil-driven through earthworms and springtails (Zhu et al., 2018b), because bioturbation can cause the migration of microplastics in soil. For example, when earthworms were exposed to soil surface litter containing different concentrations of low-density polyethylene (LDPE) for 2 weeks, it is found that the microplastics in soil can migrate with the disturbance of earthworms (Huerta Lwanga et al., 2017). When the concentration of microplastics in the surface litter is 7%, 73.5% of the surface microplastics migrate downward under the disturbance of earthworms (Huerta Lwanga et al.,

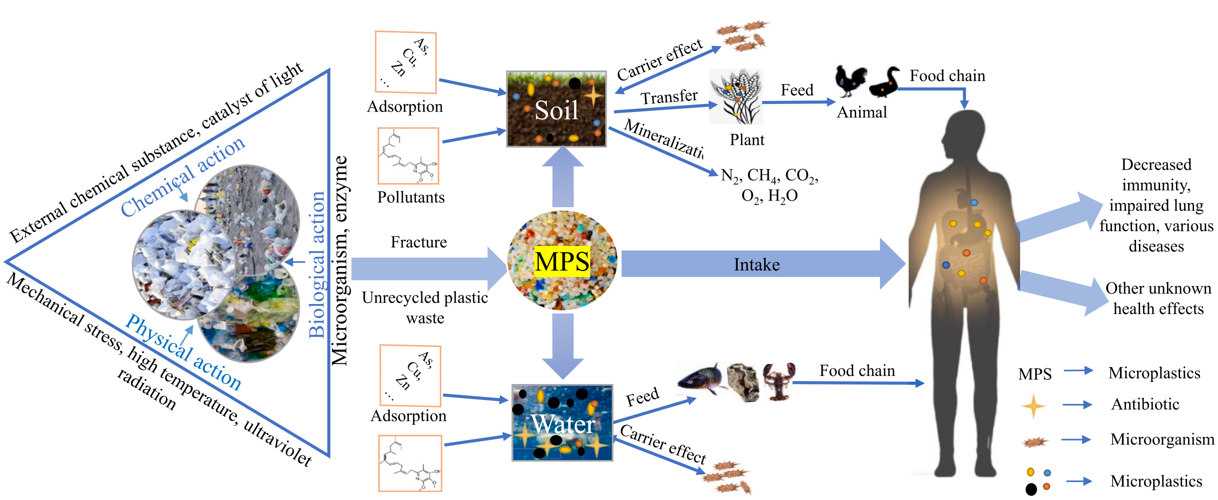

Fig. 5. Schematic diagram of the plastic migration process in the environment.

2017). Wang et al. simulated the longitudinal migration of microplastics in constructed wetlands and found that the presence of earthworms could make the microplastics in the medium more prone to longitudinal migration (Wang et al., 2021d). The presence of microplastics in the soil leachate indicates that earthworm activities can affect the longitudinal migration of microplastics (Huerta Lwanga et al., 2017). And water infiltration, soil animal excretion, and plant root growth can promote the horizontal and vertical migration of microplastics (Allouzi et al., 2021; Li et al., 2020a). Li et al. analyzed the vertical migration of microplastics along with the soil profile under the corn root system and found that the corn root system may help the microplastics move upward in the middle layer, and the crop roots tend to move the microplastics upward or keep them in the soil layer. In contrast to the downward migration of microplastics caused by water infiltration and soil animal activities (Li et al., 2021a). At the same time, the roots of crops can also ingest microplastics, and the microplastics that enter the crops through the roots can migrate to the stems and leaves of the crops (Liu et al., 2021a). Through the transmission of the food chain, this part of microplastics may eventually enter the human body (Allouzi et al., 2021). Some of the microplastics entering the human body can remain in the human body, and the rest can be excreted, researchers have found a variety of microplastics in human feces (Yan et al., 2022). Manures are applied to agricultural soil as fertilizer, causing some microplastics to return to the soil system. This shows that the migration mode of microplastics in soil is complex and diverse. However, the intake and excretion of organisms, the carrying of wind and rain, and the influence of human external forces may be the main migration pathways of soil microplastics.

Previous studies have shown that microplastics in soil could migrate vertically through plant root growth or plant pullout, water infiltration, regular farming activities, soil animal intake and excretion, and the excavation behavior of some animals (Huerta Lwanga et al., 2017; Wang et al., 2021d; Wu et al., 2020). The life activities of insects, the hunting activities of the food chain, and the effect of wind can promote the horizontal migration of microplastics in soil (Li et al., 2020a). To date, existing studies have not conducted in-depth discussions on the migration mechanism of microplastics in the soil environment, and there is almost no relationship between the changes in the soil environmental quality and the migration of microplastics, and theoretical research and experimental tests are needed to explore.

4.2. Migration of microplastics in the water environment

External forces such as ocean currents, wind, and rivers can affect the migration process of microplastics in the water environment (Ibrahim et al., 2021; Tamminga and Fischer, 2020). Environmental factors such as natural organic matter, minerals, pH, ions, and ionic strength in water can also affect the migration behavior of microplastics (Sharma et al., 2021). Microplastics were found in both plateau lakes and deep-sea sediment (Feng et al., 2021). Therefore, studying the migration mechanism of microplastics in the water environment is the key to solving the problem of microplastic pollution. Studies have found that invertebrates, zooplankton, sea turtles, and fish could eat microplastics. For example, Giani et al. collected *Mullus barbatus* and *Merluccius merluccius* from three different regions of the Mediterranean to study their intake of microplastics and found that 23.3% of fish in the gastrointestinal tract contained microplastics (Giani et al., 2019). And after being ingested by organisms, microplastics can stay in the digestive tract of organisms for a long time. They can even enter various organs and tissues through the wall of the digestive tract (Huang et al., 2021c). In addition, some studies have analyzed the feces of waterfowl species in five wetland lakes in central Spain and found that the feces of these waterfowl contained high levels of microplastics. This result indicates that although microplastics can enter organisms through biological feeding. However, only a few of them can stay in the organism or enter other organs and tissues through the digestive tract wall. Most of the microplastics can be excreted together with the excrement and returned to the water environment (Gil-Delgado et al., 2017). These results suggest that microplastics can migrate into organisms through the feeding effect of aquatic organisms in the aquatic environment (Markic et al., 2018; Neto et al., 2020; Rios-Fuster et al., 2019; Su et al., 2016; Wang et al., 2021b). By ingesting these organisms, microplastics can migrate from the ocean surface or bottom to different trophic levels (Fig. 5). Finally, some microplastics are returned to the environment through the excretion pathways of organisms at different locations, which is a possible migration cycle. This shows that aquatic biota and humans are both the migration receptors of microplastics and one of the sources of microplastics. Studies have shown that the hydrological and hydraulic characteristics of various water bodies could affect the migration direction of microplastics in the water environment. The hydrological conditions of lakes are relatively stable, after microplastics enter the lake, the low-density ones can be suspended on the surface of the water, while the high-density ones can be deposited on the bottom of the lake or suspended in deep water. These microplastics deposited on the bottom of the lake are not easily affected by the disturbance of water flow. They do not easily float to the surface of the water body after mixing with the silt at the bottom of the lake (He et al., 2021). The hydrological conditions of rivers are more complicated than those of lakes. In turbulent areas, the high-density microplastics tend not to deposit on the bottom of the river bed, but migrate downstream with the turbulent water flow (Ghayebzadeh et al., 2021), and most of the microplastics migrate in the direction of deposition at the bottom of the water body (Huang et al., 2021b). When the river flows into the area adjacent to the water source or the place where the energy of the water flow decreases, the high-density microplastics carried by the water flow can be deposited at the bottom of the river bed and no longer migrate downstream (He et al., 2021). Therefore, sediments in the reaches of the river with low river dynamics may be deposits of microplastics (Nizzetto et al., 2016). During the flood, the microplastics deposited at the bottom of the river bed can migrate with the flood and enter a new next migration cycle (Hurley et al., 2018). This suggests that runoff from catchments and rivers may be the main pathways for microplastics to migrate.

Previous studies have shown that microplastics could migrate through the food chain in the water environment (Markic et al., 2018). The hydrological and hydraulic characteristics of various water bodies can also affect the migration process of microplastics in the water environment (He et al., 2021). And as the size of microplastics continues to decrease, they can be accumulated and transmitted in different food chains and may enter the human body. At present, the migration of microplastics in the food chain has gradually become a research hotspot. However, existing studies have not yet conducted in-depth discussions on the migration mechanism of microplastics in the water environment, and theoretical research and experimental testing are needed to explore.

5. Degradation methods of microplastics

Once macroplastics enter the environment, external environmental forces (such as weathering, solar radiation) can break them up forming microplastics over time (Julienne et al., 2019). The natural decomposition of microplastics is very slow, and in the process of natural decomposition, many harmful substances (such as plasticizers, short-chain/medium-chain chlorinated paraffin, antioxidants in manufacturing, etc., which account for 70% of the plastic weight) can be released (Coffin et al., 2019). Currently, there are few experimental studies on the degradation of microplastics. Because the existing related research methods involve different biological strains, experimental conditions, and reagents, their costs and degradation efficiency are also different. As far as we know, there are few known greens and efficient degradation methods for microplastics in the environment. At present, all the degradation methods of microplastics can be mainly classified into three categories, namely physical, chemical and biological degradation methods. The chemical photodegradation method is often used in the research on the degradation of microplastics, because compared with the other two methods, the degradation efficiency of the chemical photodegradation method is higher than that of the physical method, and the experimental process is simpler than the biological method, so it has attracted the attention of researchers. The comparison of the degradation methods studied in recent years is shown in Table S2, which briefly summarizes the advantages and disadvantages of the types of microplastics studied recently and their degradation methods.

5.1. Physical degradation

The physical degradation of a polymer refers to the degradation process of the polymer being exposed to physical conditions such as oxygen, water, pollutants, different temperatures, and mechanical forces, which causes the carbon chain of the polymer to gradually break and produce small molecules. For example, Ni et al. pyrolyzed the microplastics in the sludge at five different temperatures (150, 250, 350, 450, and 500 °C). The result showed that when the pyrolysis temperature reached 450 °C, the aggregates in the sludge PE and PP microplastics were completely degraded, and when the pyrolysis temperature was increased to 500 °C, there are no tiny (10–50 μm) microplastics residues (Ni et al., 2020). This shows that the pyrolysis treatment has a higher mitigation effect on the microplastics in the sludge, and the small microplastics are easier to be removed by pyrolysis. Song et al. simulated the effect of pyrolysis aging on PE, PP, and PVC microplastics, it was found that PE and PP after pyrolysis aging treatment could randomly fracture. For PVC microplastics, the thermal aging process can cause structural defects and make the color of PVC light yellow, and after 128 h of pyrolytic aging, the maximum weight loss rate drops by 35.8% (Song et al., 2021). Studies have also evaluated the physical degradation of PS microplastics caused by stirring at room temperature (23 °C) for 1 week and found that in ultra-pure deionized water, with simple stirring, chemically stable PS microplastics could be degraded from micron to nanoscale (Mekaru, 2020). Microplastics are also degradable by water and sediment movement (hydrolysis and mechanical wear). Factors such as oxygen, temperature, salt concentration in water, and sediment size can affect the degradation of microplastics (Born and Brull, 2022). In another study of the co-pyrolysis of four actual plastics (HDPE, LDPE, PP, and PS) and tires, it was found that compared with the co-pyrolysis of plastics and tires, the pyrolysis temperature range of a single plastic was narrower, and the co-pyrolysis was conducive to the degradation of microplastics (Hu et al., 2020). The latest study found that focusing the light beam through a glass ball can also melt microplastics at high temperatures (Wang et al., 2022).

The physical degradation method has the advantages of simple and easy operation, low cost, and short reaction time. The disadvantage is that the degradation effect is not ideal and the scope of application is narrow. It is usually used in combination with other methods. The physical pyrolysis method has shown good ability in treating microplastics in wastewater and sludge. The pyrolysis temperature is different, and the degradation efficiency is also different. Simulating the oxidation and aging environment that is conducive to the degradation of microplastics, which can accelerate the degradation of microplastics (Iniguez et al., 2018). In the future, it is necessary to further study the environmental physical factors that play a key role in the physical degradation process, explore co-pyrolysis methods that are beneficial to the degradation of microplastics, and study the similarities and differences of various microplastics in the degradation process. These studies may be the focus of future research and help evaluate the degradation performance of different microplastics and the environmental risks faced by organisms.

5.2. Chemical degradation

The chemical degradation method uses external chemical substances, and peroxide and carbonyl groups added during the reaction to cause chain scission or crosslinking of the polymer. It can reduce the molecular weight of the polymer and the physical properties of the polymer material, thereby achieving the purpose of degradation. For example, Miao et al. proposed a Fenton-like technology (EF-like) based on TiO_2/graphite (TiO_2/C) cathode. This technology was electrolyzed at −0.7 V concerning Ag/AgCl for 6 h at a constant potential. Its dechlorination efficiency reached 75%. It underwent reduction and dechlorination by the cathode and at the same time oxidized the hydroxyl radicals, showing excellent performance in the degradation of PVC (Miao et al., 2020). Some researchers have prepared mixed PLA and PE/TiO_2 into a nanocomposite film under certain conditions, by adding TiO_2 nanoparticles to the PLA/PE film to reduce the life of the polymer and then irradiate it by simulating sunlight. The experiment results show that TiO_2 promotes the degradation of PLA and PE and affects the level of polymer organization (da Silva et al., 2014). In addition, after adding a photothermosensitizer (containing silver nanoparticles and cobalt stearate) to the LDPE to make a composite material, the sunlight can also be used to degrade the PE (Firestone et al., 2019). Lin et al. found that compared with the conventional dose of ultraviolet radiation, excessive ultraviolet radiation (3600 mJ cm^{-2}) can lead to obvious morphological changes (such as cracks, wrinkles, and protrusions) of PS, PVC, and PET (Lin et al., 2020). This phenomenon was attributed to the chemical bond fracture of microplastics caused by excessive ultraviolet radiation. For example, UV radiation can break the C–C and C–H bonds of microplastics, thereby degrading them (Born and Brull, 2022).

The advantage of the chemical degradation method is that it can not only use external chemical substances to achieve the purpose of degradation but also use abundant natural light for the mineralization process. Moreover, solid high-efficiency photocatalysts can also be used for photocatalytic degradation, to achieve the purpose of degradation. The chemical degradation process also helps researchers analyze the degradation mechanism. Its disadvantages include high cost, unsatisfactory degradation effect, and difficult preparation of solid high-efficiency photocatalysts. These shortcomings may limit the application of chemical degradation in actual large-scale production. The development of high-efficiency catalysts with easy preparation, low cost, and good degradation effect is an important direction of future research. Meanwhile, new chemical degradation methods should be continuously explored to find the most favorable chemical conditions for chemical degradation. Which is important for reducing the impact of microplastics on the environment.

5.3. Biodegradation

The biodegradation method refers to the use of original or inoculated microorganisms to degrade or metabolize microplastics and convert them into harmless end products. Degrading microplastics through microbial technology can provide a new idea for the treatment of microplastics in the environment. For example, Álvarez-Barragán et al. screened out 8 strains that can effectively degrade polyurethane. Research has shown that the degradation rate of polyurethane is 87% after 14 d of cultivation with *Pseudocladida T1.PL.1.* The fungus-treated foam has a melting and thinner cell wall structure than the untreated foam, indicating that the fungus has a biodegradable effect on polyethylene-polyurethane foam (Alvarez-Barragan et al., 2016). Some researchers have also found that the terrestrial snail black breast snail could also decompose polystyrene foam (Song et al., 2020). Auta et al. isolated *Bacillus 27* and *Rhodococcus 36 strains* from mangrove sediments. After they were cultured on a medium injected with PP microplastics for 40 d, it was observed that the weight loss rates of *Rhodococcus 36 strain* and *Bacillus 27 strain* were 6.4% and 4.0% respectively. This change shows that these bacteria have the characteristics of degrading PP microplastics (Auta et al., 2018). And after growing *Bacillus cereus and Bacillus gottheilii* in a medium containing different microplastics as the sole carbon source for 40 d. The weight loss of PE, PET, and PS treated by *Bacillus cereus* was 1.6%, 6.6%, and 7.4%, respectively. The weight loss of PE, PET, PP, and PS treated by *Bacillus gottheilii* was 6.2%, 3.0%, 3.6%, and 5.8%, respectively (Auta et al., 2017). These changes all indicate that different biological strains have the potential to degrade different microplastics, and the degradation effects are also different. Ishii et al. used fungi to degrade polyethylene succinate microplastics and found that on a medium with polyethylene succinate as the sole carbon source, under aerobic conditions at 30 °C, the degradation rate of mesophilic *strain NKCM1003* to polyethylene succinate was 21 ± 2 μg cm^{-2} h^{-1}. This degrading fungal strain belongs to the phylum Ascomycota and grows well on the culture medium, indicating that it can mineralize polyethylene succinate. The SEM image table proves that the microplastics gradually degrade from the amorphous state on the surface (Ishii et al., 2007). Gamma irradiation-assisted fungal White-rot fungus *Bjerkandera adusta* can also degrade PP composite materials. Under the action of selected strains, γ-irradiation can degrade PP (Butnaru et al., 2016). Park et al. put the bacteria in an aqueous medium containing PE microplastics as the sole carbon source to grow for 60 d and found that the dry weight of microplastics was reduced by 14.7%. Moreover, it was discovered that the dominant bacteria that degrade PE microplastics were mainly *Bacillus* and *Paenibacillus* (Park and Kim, 2019).

In the biodegradation process, the degradation effect can be better when physical technology is combined with biological treatment. The biodegradation method has the advantages of simple and easy operation, low operating cost, flexibility, environmental protection, cleanliness, and relative safety. The disadvantage is that the environmental factors are complex and changeable, which may lead to uncertainty in experimental data. If researchers want to use this method on a large scale, they need to continue to explore to provide more reference data. The key step of biodegradation is to select suitable biodegradable strains. Different biodegradable strains used have different degradation efficiency. It is necessary to understand the living habits, living conditions, and degradability of degrading strains for the degradation of microplastics. Therefore, further exploring more undiscovered strains and microorganisms that can degrade microplastics is the focus of the next research. Moreover, reducing the pollution of microplastic to the environment is an important direction for future research.

6. Conclusions and future perspectives

Microplastic pollution and its ecological effect have become a hotspot in global environmental scientific research. This paper systematically reviews the distribution of microplastics and discusses the biological effects and migration behavior of microplastics in the water and soil media. The degradation methods of microplastics are also systematically summarized. It is found that due to the changeable environmental factors, complex biological systems, and diverse functions, the current research is mainly carried out in the laboratory. The experimental conditions are significantly different from the actual environment, and the research objects are only limited to the analysis of a few organisms. Are the research results generally representative? Can the application be promoted in the actual environment? These issues have not yet been clearly clarified. Especially in terms of degradation methods, there are few studies on the degradation of green and high-efficiency plastics, especially methods that specifically degrade microplastics that have not been extensively studied. However, hundreds of tons of plastic are released into the environment every year. Thus, continuing to explore the green and efficient degradation methods of microplastics is the focus of the next research. In addition, how to conduct more in-depth research in this field based on existing research is the key difficulty that needs to be solved urgently. To better deal with the health risks of microplastics being widely exposed to the natural environment, the following research should be strengthened:

1. To reveal the accumulation, migration, and degradation of microplastics in the environment, it is necessary to accurately analyze the occurrence and contribution of microplastics in the environment. Meanwhile, it can also provide a reference for the prevention and control of microplastic pollution in the environment.
2. The research on the release characteristics of chemical additives from microplastic in the environment essentially needs to be strengthened. Revealing the release characteristics of microplastics chemical additives under different environmental conditions will be an important research direction. Besides, the interaction between microplastics and pollutants and the mechanism of compound pollution in the environment should be strengthened.
3. Due to the difference in size, the current research methods and experimental results of microplastics are not completely applicable to nano plastics. It is requisite to advance the research on the analysis, identification, separation, and degradation methods of nano plastics in the environment. It is urgent to establish matching identification analysis, separation, and degradation methods based on the characteristics of nano plastics.
4. The current research adopts laboratory simulation methods, which are mainly based on index tests such as reproduction rate, survival rate, and growth rate. It is necessary to conduct in-depth research on the toxicological effects of microplastics on the environment. In the future, it can try to research the toxicological effects of microplastics on organisms in the environment and the migration mechanism in the body through real environmental practices.
5. Establishing and improving the separation and analysis methods of microplastics in soil and exploring the methods of degradation would be the trend in the future. At present, the separation of microplastics in soil is mainly based on the related methods of separating microplastics in sediments. Due to the diversity of soil properties and the complexity of microplastic properties, it is indispensable to research the separation, analysis, and identification methods of different types of microplastics for different types of soils.

Declaration of competing interest

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.

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Appendix A. Supplementary data

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