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Review

Microplastic Pollution in Water Systems: Characteristics and Control Methods

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Abstract: Microplastics have been widely detected in the natural water environment, which brings inevitable risks to the water ecosystem and human health. However, the understanding of the potential impact of microplastics on aquatic animals, plants, and human health is still limited, and technical methods to control microplastic pollution in natural water are still rare. Hence, this paper summarizes the progress of research on microplastic pollution in water systems in terms of microplastic source, attributes, distribution characteristics, environmental effects, and prevention and control methods according to the relevant research reports on water microplastic pollution. It also expounds the basic ways for the prevention, control, and treatment of water microplastics, and looks forward to the research direction of water microplastic pollution in the future. The results show that the abundance of fresh water microplastics in China is higher than that in other regions, but the pollution level of marine microplastics is at the middle level. Compared with other countries, the pollution degree of microplastics in aquatic organisms in China is at the middle and lower level, but the spatial heterogeneity is more obvious. Through hydraulic control and the substitution of degradable plastic products, water microplastic pollution can be greatly reduced. This paper can provide a reference basis for the formulation of microplastic pollution prevention and control in China.

Keywords: microplastics; distribution characteristics; environmental effects; pollution prevention and control; microplastic characterization and detection techniques

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1. Introduction

Plastic is widely used in our daily life and industrial production due to its lightweight, durable, corrosion-resistant, and economic characteristics. With the increase in plastic production and usage, the problem of environmental pollution caused by plastic waste is becoming more and more serious [1,2]. According to statistics, coastal countries generated about 275 million metric tons of plastic, of which 4.8 to 12.7 million metric tons entered the ocean [3]. A United Nations (UN) estimate revealed the presence of about 51 trillion plastic debris in the seas, a value 500 times greater than the amount of stars in the entire galaxy [4,5]. Among them, a class of plastic particles less than 5 mm, known as microplastics, causes widespread concern in terms of its impact on water ecology. These millimeter- or even micron-sized plastic debris not only clog the organs and roots of plants and animals [6], but also adsorb hydrophobic organic contaminants in water [7,8], resulting in complex pollution and even toxicity enrichment problems in the ecosystem [9]. The source, migration, and influence characteristics of microplastics in water are shown in Figure 1. In the second Session of the United Nations Environment Conference in 2015, microplastic pollution was listed as the second major scientific problem in the field of environmental and ecological science, along with global climate change, ozone depletion, and other major global environmental problems [10]. In May 2016, UNEP released an assessment report on global marine microplastic pollution, urging countries to strengthen the research and regulation formulation of marine microplastics as soon as possible [11]. In the same year, China included "Marine microplastic monitoring and eco-environmental benefit assessment study" in the National Key Research and Development Program of the Ministry of Science and Technology, and launched the offshore microplastic monitoring work. In 2017, China expanded its monitoring of microplastics for the first time to include the ocean and polar areas. As a emerging pollutant, the environmental pollution caused by microplastics has attracted extensive attention from researchers both in China and abroad.

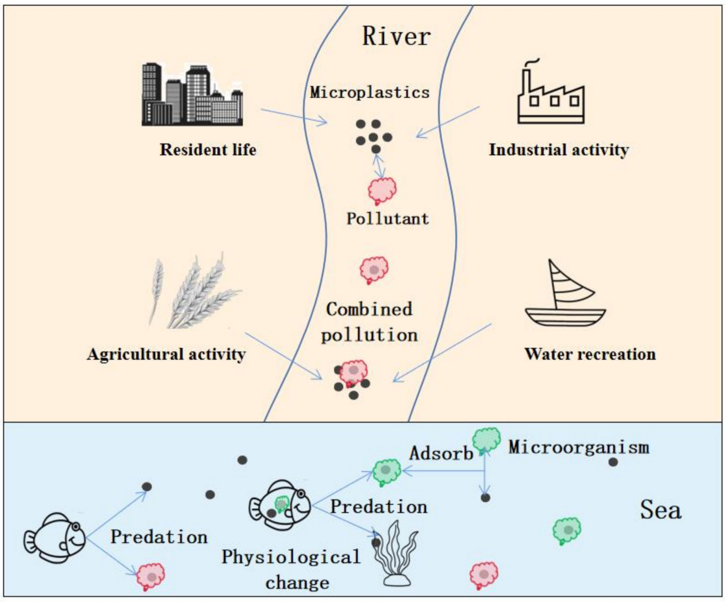

Figure 1. Source, migration, and impact of microplastics on the environment.

2. Source, Attributes, and Distribution Characteristics of Microplastics

2.1. The Composition and Source of Microplastics in Water

The sources of microplastics in water include not only the dumping and burying of plastic waste in production and daily life, but also the transport and entrainment of plastic waste caused by natural disasters such as hurricanes and tsunamis [12,13]. Common sources of microplastic particles can be divided into two categories: primary and secondary microplastics [14,15]. Primary microplastics refer to micron plastic particles produced by industry [14]. And secondary microplastics are the plastic particles produced through the physical and chemical fragmentation and decomposition of large plastics [15].

Primary microplastics are usually regular bodies, mostly plastic particles of a certain size prepared artificially to meet special needs, mainly including facial cleanser additives, bath gel additives, toothpaste additives, shaving foam additives, and some industrial raw materials [16]. Secondary microplastics mainly come from the physical crushing of bulk plastics, including rock grinding, hydraulic scouring, etc. The shape of secondary microplastics is usually irregular [17]. Most of the primary microplastics are discharged into the sewage pipe network with the sewage, then into the natural water body, and finally into the ocean under the action of river transport; the total transport amount accounts for about 15–35% of the total amount of microplastics entering the sea [18]. Secondary microplastics account for 69–81% of the total amount of marine microplastics, mostly formed by the degradation of larger plastics such as plastic bags, bottles, and fishing nets [19]. There are reports that the absolute values of microplastics released into the ocean from seven regions, including Africa and the Middle East, China, East Asia and Oceania, Europe and Central Asia, India and South Asia, North America and South America, range from 134 to 281 kg per year, with per capita releases in each region ranging from 110 to 170 g per person per year [4]. In recent years, the United States, Japan, South Korea, and other countries have introduced bans on adding microplastic particles to personal care products. On 30 October 2019, the National Development and Reform Commission (NDRC) revised and released the Guidance Catalogue for Industrial Structure Adjustment (2019), which officially proposed that "the production of daily chemical products containing plastic microbeads will be banned by 31 December 2020, and the sale will be banned by 31 December 2022" [20]. The source of primary microplastics is relatively simple, and the investigation on the source of primary microplastics has been quite advanced. However, the source of secondary microplastics is relatively complex, and the morphology and characteristics of secondary microplastics change greatly after physical, chemical, and biological interactions, so it is difficult to identify the source of secondary microplastics using morphological discrimination and other methods. Wang et al. (2019) developed a set of source analytic classification systems for the quantitative analysis of microplastic sources, achieving the rapid identification of microplastic particles such as microspheres, fibers, and foam [20]. However, this method only uses part of the classification indexes, and does not describe and summarize the color and polymer components in detail, so the application scope and accuracy of the recognition method need to be improved. Recently, tools such as biomonitoring methods [21], single-molecule techniques [22], and finite-element computer simulation approaches [23] were developed for detecting microplastics in aquatic ecosystems. However, the limited availability of existing biomarkers, the complexity of calibration steps before data acquisition, and the need for large data sets related to computational cost resources limits the scope of use and application prospects of such methods. Microplastics are difficult to degrade in the natural environment and will exist for a long time. They are easy to accumulate in water and soil and form persistent pollution, thus affecting the regional ecological environment for a long time [15]. Therefore, it is urgent to identify the source of microplastics and control the total amount of microplastics that enter into rivers and seas.

2.2. The Characteristics of Microplastics in Water

The physical and chemical properties of microplastics are easily changed under the action of runoff, tides, wind, radiation, biology, and other environmental factors. Studies had shown that microplastics not only undergo changes in physical properties such as cracking and foaming in water bodies, but also changes in chemical properties such as chemical bond breakage and molecular cleavage under the influence of environmental effects, which directly affect the migration distribution law, the adsorption analysis process, and the ecological environment effect of microplastic particles in water bodies.

Microplastics migrate over long distances under the action of wind, runoff, and tides [24,25]. And microplastic undergo surface cracking, crushing, and other morphological changes, forming microplastic particles with a smaller particle size under the effect of radiation, temperature, and water turbulence [17]. Through the analysis of microplastic samples in sludge using scanning electron microscopy, Mahon et al. (2017) found that environmental effects can cause blistering, bulging, and cracking on the surface of microplastic particles [26]. Plastic waste discarded on the beach can also be broken and cracked under the action of wind, radiation, and other environmental factors, and enter the ocean under the action of rain erosion and tidal driving, resulting in persistent microplastic pollution [15]. Lambert and Wagner (2016) experimentally placed a piece of 1 cm^2 polystyrene plastic in pure water at 30 °C for 24 h, and then irradiated it with UV light at 320~440 nm for 56 days, resulting in 1.26×108 n/mL microscopic plastic particles [27]. Research has shown that light and oxidation are the main factors that induce the chemical properties of microplastics. The molecular chains of microplastic particles undergo cracking and cross-linking reactions, thereby changing the chemical properties of microplastics under the action of light [28]. Oxidation leads to the increase of oxygen-containing groups on the surface of microplastics, thus changing the surface polarity and hydrophobic characteristics of microplastics [29]. Among them, the Ico of large plastics (>20 mm) (the absorbance of carbonyl groups relative to the absorbance of methylene groups) was only about 0.1 (relative to unaged plastics), while the Ico of small and medium-sized plastics (<20 mm) could reach 0.7, indicating that the smaller the particle size of the plastic particles, the easier it was to age, and the easier it was to change the surface chemical properties [30].

2.3. The Migration and Distribution Characteristics of Microplastics in Water

Microplastics are extremely difficult to biodegrade in the natural environment, which means that microplastics discharged into water bodies can exist in those water bodies for hundreds of thousands of years. Studies have shown that microplastics are distributed in various hydrodynamic environments [31,32]. In order to solve the problem of microplastic pollution, it is necessary to clarify the migration process and distribution of microplastics.

Both environmental factors and the properties of microplastics affect the migration and distribution of microplastics in water. About 50% of the microplastics in the natural water body have a density lower than that of the water body. After this part of the microplastic particles with a lower density than the water body enter the water body, they float on the surface of the water body and drift into the ocean under the driving effect of runoff and wind stress [33]. Subsequently, some of these microplastics migrate into the ocean circulation under the action of ocean currents and wind, forming plastic waste accumulation areas. For example, in "the North Pacific Garbage Patch", located in the eastern part of the North Pacific subtropical circulation, there are 0.45105 to 1.29105 t of plastic floating matter, of which microplastics accounts for about 8%, and this number is increasing exponentially [34]. The other part change in density and mass under the action of microbial attachment and sediment flocculation, etc., and migrate vertically to the bottom of the water body, or are even buried in the sediment [35]. The microplastic particles entering the sediment persist under the action of low temperature and low oxygen, thereby increasing the threat time of microplastic particles to the aquatic ecosystem. Unlike the migration and distribution characteristics of low-density microplastic particles, sedimentation, stranding, and burial are the main movement forms of high-density microplastic particles in water bodies [36]. In addition, topography and the special hydrodynamic environment of the estuary (tidal reciprocating flow, density flow, etc.) are also important factors affecting the migration and distribution of microplastics [37,38]. In fact, under the influence of multiple complex environmental factors, microplastics undergo complex migration and change processes such as transport, suspension, settlement, resuspension, re-settlement, stranding, and burial under the action of runoff, tide, wind, and terrain [39]. The migration and distribution of microplastic particles in water is a complex system, and it is often difficult to accurately determine the migration and distribution of microplastic particles in water simply based on the properties of microplastics and the characteristics of the external environment.

3. Environmental and Ecological Effects of Microplastics

3.1. The Contamination-Carrying Characteristics of Microplastics

In essence, microplastics are a class of granular polymer compounds, which have the characteristics of a small particle size, large specific surface area, monomer polymerization, and surface hydrophobicity. They can be used as sources of and sinks for pollutants, affecting the migration and distribution of pollutants in environmental water bodies. Studying the pollution-carrying characteristics of microplastics is of great significance for identifying and controlling the migration path and distribution range of pollutants.

Plastics are polymer compounds that are polymerized from monomers as raw materials, and contain plasticizers, stabilizers, lubricants, and other additives. During the polymerization process, it is difficult for plastic compounds to achieve 100% utilization of monomeric substances. At this time, when the plastic waste (microplastics) enter the environmental water body, the remaining monomer substances are released as pollutants under the action of the concentration gradient [40,41]. Researchers have detected organic pollutants such as chlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), as well as bisphenol A (BPA) and antibiotics from the surface of microplastic particles in freshwater, oceans, and sediments, and found that the concentration span of organic pollutants carried on the surface of different microplastic particles at the same location even reached 1–10,000 ng/g [42], indicating that microplastic particles would leach and release organic pollutants into environmental water bodies, as shown in Figure 2. In addition, due to their small specific surface area and hydrophobicity, microplastics could also adsorb other hydrophobic pollutants in water, including: persistent organic pollutants, heavy metal ionic pollutants, etc., resulting in toxic enrichment and forming a more serious composite pollution problem [42,43]. The particle size, color, and material of microplastics can affect their adsorption capacity for persistent organic pollutants [44–46]. Among them, the smaller the particle size, the stronger the adsorption capacity of microplastic particles to organic pollutants [44]; the adsorption capacity of black microplastics to persistent organic pollutants (POPs) is stronger than that of microplastic particles of other colors [45]; aging can change the surface roughness and crystallinity of microplastic particles, thereby affecting their ability to adsorb and desorb organic pollutants [46]. In addition, environmental factors, including salinity, temperature, pH, etc., also change the adsorption and desorption processes of some microplastic particles to water organic pollutants [47]. In general, microplastics can adsorb and carry persistent organic pollutants and ionic heavy metal pollution in environmental water, thereby changing the migration and distribution characteristics of pollutants in the water environment, and even the transfer and transformation paths in the ecosystem.

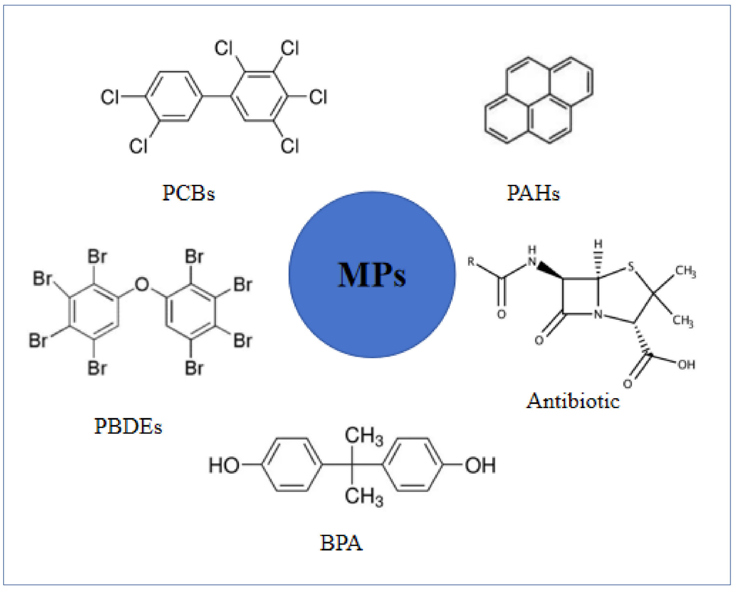

Figure 2. Microplastics adsorb organic pollutants.

3.2. The Carrier Effect of Microplastics

After microplastics enter the water body, they are easily occupied by microbial communities, forming a "plastic circle" micro-ecology. The "protoplasmic" biofilm formed by the attachment of microorganisms does not only affect the migration and distribution of microplastics in the water environment, but also the structural characteristics of the biological community in the water body, and even causes ecological disturbance problems [46].

As an isolated carrier, microplastics can easily interact with water microbes to form a "plastic circle" ecosystem [46], providing new habitats for the growth and reproduction of microbes in water. However, due to environmental characteristics and the physical and chemical properties of microplastics, water microorganisms have a certain selectivity for the attachment of microplastics [48]. In rivers, bacterial assemblages colonizing microplastic surfaces are significantly fewer than those in water bodies and water suspensions [48].

Microplastics can also serve as a fortress for microorganisms, resist the impact of external environmental changes on the growth and reproduction of microorganisms, and even help microbial communities adapt to new environments [49]. In addition, microplastics can also be used as breeding and hard spawning grounds for certain plankton species, such as sea strider and plasmodium filarii, to improve biodiversity in specific waters [50]. However, they may also carry some alien microbial species into new environments, causing biological invasion, and even expanding the spread of certain pathogens [51], causing changes in the structure and function of regional ecosystems. In addition, the attachment of microorganisms can also change the migration and movement of microplastics in water [52]. Analyzing the characteristics of microplastic carriers and clarifying the interaction between microplastics and microorganisms is the key to solving the problem of microplastic pollution in water bodies. However, there are still few reports on the carrier effect of water microplastics and their interaction with microorganisms, and further research is needed.

3.3. The Ecological Effects of Microplastics

Microplastics are ubiquitous in the water environment. They have a wide distribution range, small particle size, and high color recognition rate. They are easily eaten or captured by aquatic animals and plants in environmental waters, causing ecological damage [53–55]. According to statistics, more than 220 aquatic animals and plants in nature could accidentally eat or capture microplastic particles. The species category involves all trophic levels of the aquatic ecosystem, including producers such as zooplankton and phytoplankton, as well as fish and turtles, whales, and other predators [56].

Microplastic particles captured by plants can block light and reduce the chlorophyll content of green plants in water such as algae, and affect the light absorption efficiency and photosynthesis rate of green plants [53]. Experiments showed that 1.8–6.5 mg/L of 20 nm microplastic particles could inhibit the photosynthesis of Scenedesmus, and could be absorbed into the algal cells, resulting in oxidative pressure, causing mechanical breakage and the fragmentation of the cell wall, affecting the material exchange and genes of cell expression, and even causing algal death [57]. It is very easy for some aquatic organisms with low nutrient levels to indiscriminately ingest microplastics because they do not have the ability to identify substances; this can cause organ blockage or knotting [56], and inhibit or even destroy their life rhythms [58]. For example, after eating microplastics by mistake, a large flea produces an ecological protein corona, which leads to the disturbance of the intestinal digestive system of the flea [58]. In addition, some coelenterates, benthic organisms, and even fish can also ingest microplastics by mistake; these can easily accumulate in the gastrointestinal tract, resulting in decreased feeding rate and digestive system damage, and even spread to the fins and muscles through the blood system. In tissues, microplastics directly affect the growth and development of aquatic animals [59–61]. Microplastics are transmitted, accumulated, and amplified through the "algae–phytoplankton–macrovertebrates" aquatic food chain, and eventually even threaten the health of the top consumers, "humans". Microplastics can affect aquatic animals and plants at different trophic levels, and different exposure methods, plastic properties, and species forms may lead to different effects. However, research on the biological effects of microplastic pollution in the academic community is still in its infancy, and the tracking of the transfer path of microplastics, the analysis of genotoxicity, and the multi-dimensional analysis of ecological effects still need to be strengthened.

4. The Current Situation of Water Microplastic Pollution in China

4.1. The Occurrence of Microplastics in Water Bodies

China is a major plastic producer and consumer, and is considered to be one of the countries with the largest land-based plastic waste emissions in the world [62]. Studies have shown that microplastic pollution in water bodies in China may be very serious, especially in the environmental water bodies adjacent to urban areas, where there may be a large amount of microplastic waste; the total amount of microplastics is nearly one to three orders of magnitude higher than the abundance of freshwater microplastics in other countries [63–68]. In view of this, China began to pay attention to and study microplastic pollution in water in 2013, and in 2016, for the first time, "Marine microplastic monitoring and ecological environmental benefit assessment" was included in the National Key RESEARCH and Development Program of the Ministry of Science and Technology of the Marine Link security special. The occurrence and pollution of microplastics in the Yangtze River estuary was first reported by East China Normal University in 2014. It was pointed out that the abundance of microplastics in rivers, lakes, and seas in China has an obvious spatial heterogeneity. The average abundance of microplastics is 1.8 to 2.4 n/L in freshwater environment in China [69], and the average abundance of microplastics is about 0.9 n/L in estuaries and inshore waters [69], indicating that freshwater in China is seriously polluted with microplastics. The abundance of microplastics is much higher than that in estuaries and offshore waters, which may be caused by the large population density and large plastic usage in mainland China, as shown in Table 1. In addition, a study compared China and other countries in terms of the abundance of microplastics in water environments, and the results showed that the freshwater microplastic abundance was higher than other parts of the world, but marine plastic pollution was at the medium level, proving that in recent years, marine plastic and plastic pollution control actions have been effective [70] in China.

Table 1. Microplastic abundance in typical rivers, lakes, and seas in China.

Region	Size	Abundance	Source
Yangtze Estuary	1.2 μm–5 mm	4137.3 ± 2461.5 n/m^3	[64]
East China Sea	1.2 μm–5 mm	0.167 ± 0.138 n/m^3	[64]
Bohai Sea	330 μm–5 mm	0.33 ± 0.36 n/m^3	[65]
Pearl River Estuary	50 μm–5 mm	8902 n/m^3	[66]
Taihu Lake	333 μm–5 mm	3.4~25.8 n/L	[67]
Three Gorges Reservoir	112 μm–5 mm	3407.7×10^3~13617.5×10^3 n/km^2	[68]
Average abundance of microplastics in freshwater	/	1.8~2.4 n/L	[69]
Average abundance of microplastics in estuaries	/	0.9 n/L	[69]

4.2. The Occurrence of Microplastics in Aquatic Organisms

A number of studies have shown that common economic shellfish and fish in China have ingested microplastics by mistake [56,59]. Researchers also detected the presence of microplastic particles in shellfish and fish from offshore waters, estuaries, lakes, and rivers, confirming the severity of microplastic pollution in water bodies in China. Among them, the abundance of microplastics was 1.1 to 7.2 n/piece in the digestive tract of Chinese offshore fish [71]; the abundance of microplastics in marine shellfish ranged from 0.9 to 4.6 n/g [72]; the abundance of microplastics was 2.0 to 15.0 n/piece in fish of Qinghai Lake [73]; the abundance of microplastics was 1.5 to 2.7 n/g in wild clams in the Pearl River Estuary [74]; and the abundance of microplastics ranged from 0.4 to 5.0 n/piece in clams from 21 waters in the middle and lower reaches of the Yangtze River [75]. It is worth pointing out that the abundance, size, and color of microplastics were very similar to the occurrence characteristics of microplastics in clams in water environment in sediments, and could be used as indicators of microplastic pollution characteristics in freshwater sediments [75]. However, whether clams could be used as indicators of microplastic pollution in water environment has not been determined. Compared with the results of other countries' investigations, microplastic pollution in aquatic organisms in China is still at the middle and lower level at present, but the spatial heterogeneity is obvious, and the formulation of control and management plans should be considered in accordance with regional status.

5. Research on Microplastic Pollution Prevention and Control Methods

5.1. Microplastic Removal and Control Methods in Wastewater

In view of microplastic pollution in water, a large number of microplastic control and treatment technologies based on physical, chemical, and biological methods have been developed and constructed in the field of environmental engineering, and have been verified and applied in practical projects. Relevant studies have reported that the interception (rapid sand filtration, membrane filtration, etc.) and sedimentation processes (flocculation sedimentation, coagulation, etc.) of sewage treatment plants could effectively treat the microplastic particles entering the sewage treatment plants, with a treatment efficiency of up to 40~99.9% [76]. Among them, the removal rate of microplastics could reach 99.9% in the effluent of primary processes using the MBR method, and the removal rate of microplastics could reach 97% and 95% in the effluent of secondary processes using the fast sand filter and dissolved air float methods. Although wastewater treatment plants can reduce the total amount of microplastics into rivers to a certain extent, the total amount of microplastics carried by the larger daily water volume is still not negligible. In addition, UV irradiation can also accelerate the degradation of microplastics to a certain extent, but the time required for complete degradation is still tens or hundreds of years, and the degradation rate of microplastic particles in water is slower than that of microplastic particles in land and air [77]. Another promising method for microplastic removal is biological removal. Studies have shown that there is a certain number of insects and microorganisms in nature that can convert microplastic fragments into carbon dioxide, water, and biomass, which is considered as a possible effective way to solve the problem of microplastic pollution [78–80]. However, at present, research on microplastic degradation organisms mainly focuses on the terrestrial environment, and there are few reports on the study of microplastic degradation organisms in the water environment. Studies on the microbial degradation of marine microplastics mainly focus on the isolation of microplastic-degrading strains [81], and there have been no reports on the degradation characteristics of microplastics in water and the metabolic mechanism of bacterial strains. Reportedly, the microorganisms capable of degrading microplastics have reached 30 genera, and the main degradation object involves polystyrene (PS), plastic, polyethylene (PE), polypropylene (PP) plastic, polyurethane (PUR), polyethylene terephthalate glycol plastic(PET), polyvinyl chloride (PVC) plastic, and other plastic products. Recently, some scholars found a new way to achieve the collection and treatment of microplastic particles in water bodies by means of multi-disciplinary and multi-technology integration (water conservancy + environment). In this method, microplastics in river channels and offshore waters are concentrated at a certain point or area by changing the hydraulic properties and adding structures [82], and interception belts are laid at the main paths and key points of migration and retention of microplastics to achieve the effective filtration, collection, and capture of microplastic particles in water bodies. This method provided a new idea for the collection and treatment of microplastics in water.

5.2. The Green Degradable Alternative Technology

In recent years, many international and domestic organizations and units have issued a series of policies, regulations, and suggestions on microplastic pollution. Governments and enterprises around the world have also expressed their support and determination to solve the problem of disposable plastic pollution. However, the implementation effect is not obvious, plastic production and consumption are still high, and the total amount of microplastics has not been reduced from the source. At this time, actively looking for alternatives to traditional plastic becomes the key to solve microplastic pollution. In the context of global plastic restriction, the green degradable plastic industry has ushered in a golden period of development, and its research and development and application have been welcomed by environmental workers. According to 2018 statistics, the global demand for biodegradable plastics in 2014 was 297,000 tons, and the global demand for biodegradable plastics in 2018 was 360,000 tons, corresponding to a market size of 1.1 billion dollars. It was predicted that the global demand for biodegradable plastics in 2023 would increase to 550,000 tons. At present, a variety of degradable plastic products is applied to practical production and life, including photodegradable plastic [83], biodegradable plastic, photodegradable-biodegradable plastic [84], etc. Light-degradable plastics, referring to the lighting condition that can cause the natural degradation of plastic products, include plastic products that could absorb ultraviolet light and abate molecular bond energy. Large pieces of plastic products are broken into small pieces of microplastic particles, and then react with oxygen in the air, and are degraded into carbon dioxide and water. The main types of such products include copolymer plastics containing carbon monomer and olefin monomer synthesis, and general plastics with photosensitizers. Biodegradable plastics include completely biodegradable plastics and destructive biodegradable plastics, of which completely biodegradable plastics are mainly made of natural polymer such as starch, cellulose, protein, etc., or similar natural polymers made from synthetics; this kind of biodegradable plastics are completely biodegradable, but they are not plastic. Destructive biodegradable plastics refer to degradable plastic products made by mixing natural polymers and synthetic polymers. Such destructive bioplastic products could only be partially degraded, and the remaining petroleum-based plastic products may cause microplastic pollution. Another kind of representative degradable plastic is photodegradable-biodegradable material, which is a kind of hybrid material combining photodecomposition and biodegradation. It can overcome the problem of photodegradable plastic being limited by light and accelerate the degradation rate of plastic waste to a certain extent. In addition, the development and application of compostable biodegradable plastics, hydrolyzed plastics, and other new biodegradable plastics can also reduce the output of microplastics to a certain extent, and bring new opportunities for the source control and treatment of microplastic pollution.

5.3. Recycling Microplastics in Circular Economy

Another way to control the pollution of microplastics is to use microplastics as raw materials to form new bioplastics or other products through the circular economy. Previous studies have pointed out that microplastics are good energy products and carbon source materials. At 400 °C and 500 °C, the conversion of microplastics to energetic products can reach 65% and 78.4%. Microplastics can also be converted into combustible gases, such as CH_4 and CO [85]. Microplastics are considered as a renewable energy raw material to ensure energy sustainability, which may solve the source and environmental impact of microplastics from the perspective of the source and environmental cycle. Some studies also reported that microplastics can be degraded and converted into biodegradable polymers, which forms the core of converting waste into biopolymers to be integrated into the circular economy [86]. The recycling and utilization of microplastics through the circular economy system has been recognized as a potential and efficient way to solve the pollution of microplastics, but research on this convenience is still in its infancy [87]. Some problems continue to exist. The problem is mainly related to the identified pollutants associated with the degradation of microplastics; that is, the presence of additives and adsorbed pollutants affects the recycling of microplastics, especially their use as a biological carbon source and degradable plastics. Another potential problem is how to efficiently collect and separate microplastic particles before converting and degrading microplastics through the circular economy. Therefore, it is very important to analyze the source sink path and key emission points of microplastics through the circular economy system to achieve the collection and management of the key emission environment of microplastics, which is also an important research point that needs to be addressed in the future.

6. Summary and Outlook

The risks to ecology and human health posed by the microplastic pollution of the environment have attracted extensive attention from researchers in China and abroad. Researchers have carried out a series of studies on the sources, migration, and distribution characteristics, ecological health risks, and control methods of microplastics, and achieved some results. However, most studies focus on the explanation and analysis of the occurrence, migration, and impact of microplastics in various media and regions, and lack an in-depth analysis of the scientific mechanism of the generation, migration, and ecological effects of microplastics. Therefore, in order to deeply understand the environmental behavior of microplastics in water and solve the pollution problem of microplastics in water, the authors of this review believe that the following four aspects should be addressed in the future:

(1) Unified measurement and quantitative standards should be developed to analyze the source characteristics of microplastics

As emerging pollutants, there is still a lack of unified measurement, analysis, and quantitative standards in international research on water microplastics, and there is a problem of inconsistency between measurement standards and quantitative principles, which not only makes the secondary analysis of research results more difficult, but also weakens the sharing and conversion value of research results. Therefore, we need to formulate unified microplastic water collection, analysis, and evaluation standards, and develop better microplastics to identify quantitative technology principles, in order to facilitate the secondary analysis of research results and provide theoretical and technical support for the interaction of international researchers on this topic.

(2) The spatial and temporal distribution characteristics of microplastics in water should be analyzed by coupling numerical simulation and prototype observation

Microplastics have a short research history, and the research scope is mostly limited to some specific time and space points; in particular, the experimental and monitoring results lack the characteristics of space-time continuity. In comparison, the numerical simulation method could effectively simulate the characteristics of source and sink of regional microplastics and their migration and distribution rules, which has incomparable advantages in data continuity and consistency. Therefore, it is necessary to adopt the numerical simulation method and take that as the basis to achieve the effective analysis of the source and sink characteristics, distribution law, and the temporal and spatial variation of microplastics at line and plane levels. In addition, many key formulae and key parameters in the current microplastic migration and distribution model still rely heavily on empirical selection and manual calibration, and it is difficult to evaluate the accuracy and reliability of the prediction results. Therefore, it is necessary to continuously optimize and improve the numerical model by combining experimental and original data, so as to improve the accuracy and reliability of the model.

(3) The coupling characteristics of microplastics and pollutants need to be revealed, and the ecological health risks of microplastics in water need to be assessed

At present, research on the effects of microplastics on water ecosystem mainly focuses on laboratory mechanism experiments (high concentration microplastic stress, microplastic-pollutant combined stress, etc.), and it is difficult for the research conclusions to accurately reflect the toxic stress behavior of microplastics on natural water bodies. Therefore, it is necessary to carry out a comprehensive study on the microplastic–contaminant–microorganism compound effect and stress mechanism at the environmental concentration level, and analyze the comprehensive microplastic–contaminant–microorganism impact on various levels and cycles of the water ecosystem. A microplastic risk assessment system should be established to assess the health risks of microplastics and their combined pollution effects on ecology and human health.

(4) Green alternative plastic products should be developed and an integrated system of monitoring, forecasting, and regulating microplastics in rivers, lakes, and seas should be built

China has become the world's largest plastic industry producer and consumer, with an annual output of nearly 100 million tons of plastic. However, the recovery rate of plastic waste is only about 30%, and a large amount of waste plastic is abandoned and released into the environmental water, causing serious water microplastic pollution. Therefore, there is a need for efficient water enrichment and a high-value performance of micro-plastic repair research. Moreover, green alternatives to plastic products should be developed, and the screening of rivers and lakes in China should be carried out for highly efficient microplastic degradation bacteria. Finally, a microplastic monitoring, forecast, and control system should be built, integrating rivers and lakes. These efforts will provide theoretical and technical support for the formulation of microplastic pollution prevention and control policies in China.

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