Microplastics pollution in China water ecosystems: a review of the abundance, characteristics, fate, risk and removal

Shuyuan Tang, Ling Gao, Hongze Gao, Zongshi Chen and Donglei Zou

ABSTRACT

Microplastics pollution has been a focus for researchers in recent years worldwide, for the large quantities of plastics in production and the resistance to degradation. China’s microplastics pollution attracts much attention because of its long coastline, large population and rapid economic development. This review addresses the widespread microplastics pollution in China’s water ecosystems through available research results from recent years and analyses the abundance, characteristics, fate and risk of microplastics. This paper also discusses the current treatment technology of microplastics. The conclusions show that estuaries are severely affected by microplastics pollution; the accumulation of microplastics and adsorption of contaminants by microplastics could also lead to serious risks besides ingestion; there are few technologies that can efficiently remove microplastics pollution in sewage treatment plants. Finally, this review suggests directions for future research trends.

Key words | China’s water ecosystems, fate, microplastics pollution, risk, treatment technology

HIGHLIGHTS

- This paper collects the studies of microplastics pollution in China’s water ecosystems in recent years and evaluates the research status through a comprehensive analysis of these studies.
- This paper summarizes and improves the results of the fate of microplastics in the water ecosystem.
- This paper provides some efficient technologies for wastewater treatment plants to remove microplastics.

INTRODUCTION

The global production of plastics was about 335 million tonnes in 2016 (Plastics Europe 2008), and the annual production of plastics is estimated to rise to 33 billion tonnes by 2050 (Barrows et al. 2017); furthermore, about 10% of plastics will reach the ocean through water circulation (Thomson 2006). Researchers have found that large plastics break down into small plastics (Barnes et al. 2009), and this phenomenon has aroused the public’s attention and anxiety. The conclusion that microplastics in the marine environment are mainly terrestrial in origin has been accepted by most researchers (Auta et al. 2017). Microplastics were first detected in the North Atlantic in the 1970s (Carpenter & Smith 1972; Colton et al. 1974), and more and more marine environments have been found to contain microplastics in recent years, even the Polar regions (Barnes et al. 2009; Van Cauwenberghe et al. 2015; Woodall et al. 2014). The distribution of microplastics is influenced by the density of the particles, the location of the sources, and conveyance by ocean currents and waves (Magnusson et al. 2016).
Most researchers have defined plastic particles with sizes below 5 mm as microplastics (Betts 2008; Arthur et al. 2009; Teuten et al. 2009; Hidalgo-Ruz et al. 2012; De Sa et al. 2018), while others have set the upper size limit as less than 1 mm (Claessens et al. 2011). The value of 5 mm is more often used in recent research, while 1 mm is a more intuitive value (Van Cauwenberghe et al. 2013). The microplastics in water and sediments require centuries to be degraded and will accumulate within the neustonic habitat (Barnes et al. 2009; Ryan et al. 2009; Zarlf et al. 2011); they have now been reported in the entire marine ecosystem (Lusher et al. 2013). The small size of microplastics makes them bioavailable to organisms, from invertebrates and fish to birds and mammals (Betts 2008; Fossi et al. 2014; Murray & Cowie 2011), and microplastics may even cause risk to human health through the food web (Pellini et al. 2018). Microplastics have been reported in the entire marine ecosystem around China (Lusher et al. 2013), have the potential to accumulate contaminants on their surfaces, such as toxic metals, carcinogens and toxic substances (Bellas et al. 2020), and harmful substances in the microplastics can also be released into the environment and organism (Teuten et al. 2009).

China is the largest plastic producer and consumer in the world, accounting for 26% of the world’s total plastic production, and China also has the largest output of plastic waste to the marine environment (Jambeck et al. 2015; Zhao et al. 2018). So the marine environment around China is a hotspot for microplastics pollution research. The purposes of this review are to (1) summarize the research status of microplastics pollution in China, (2) summarize different research methods of microplastics pollution in China’s water ecosystems, thus providing a reference for maintaining the consistency of sampling and detection methods in future studies, (3) discuss the fate and removal of microplastics in the water ecosystem, providing a technical reference for the wastewater treatment plants (WWTPs) to remove microplastics.

**THE ABUNDANCE OF MICROPLASTICS IN CHINA’S WATER ECOSYSTEMS**

**Microplastics in seawater**

There are many studies on microplastics in China’s water ecosystems (Table 1), but the sampling and detection methods are not consistent. Sampling tools, sampling depth, mesh size and test equipment have important effects

### Table 1 | Microplastics abundance in seawater

<table>
<thead>
<tr>
<th>Location</th>
<th>Regions</th>
<th>Sampling Details</th>
<th>Detection Method</th>
<th>Abundance (n/m³) ± Error</th>
<th>Mesh Size (μm)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>South China Sea</td>
<td>Central</td>
<td>Deep water (200 m depth): collected by a bongo sampler with 333 μm meshes</td>
<td>FTIR</td>
<td>0.045 ± 0.093</td>
<td>333</td>
<td>Cai et al. (2018)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Surface water (0.5 m depth): taken by a pump and 5 mm, 154 μm, 44 μm meshes</td>
<td></td>
<td>2.569 ± 1.770</td>
<td>44</td>
<td></td>
</tr>
<tr>
<td>East China Sea</td>
<td>Changjiang Estuary</td>
<td>Surface water (0.5 m depth): 70 μm meshes</td>
<td>Micro-FTIR</td>
<td>231 ± 182</td>
<td>70</td>
<td>Xu et al. (2018)</td>
</tr>
<tr>
<td></td>
<td>Jiaodong Estuary</td>
<td>Surface water (0.3 m depth): taken by a pump and 333 μm meshes</td>
<td>Micro-Raman spectroscopy</td>
<td>955.6 ± 848.7</td>
<td>333</td>
<td>Zhao et al. (2015)</td>
</tr>
<tr>
<td></td>
<td>Ouijiang Estuary</td>
<td>Subsurface water (1 m depth): taken by a pump and 32 μm meshes</td>
<td>Microscopy</td>
<td>4,137.3 ± 2,461.5</td>
<td>32</td>
<td>Zhao et al. (2014)</td>
</tr>
<tr>
<td></td>
<td>Minjiang Estuary</td>
<td>Subsurface water (horizontally at the surface): taken by a Neuston net and 333 μm meshes</td>
<td>Microscopy</td>
<td>0.167 ± 0.138</td>
<td>333</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yangtze Estuary</td>
<td>Subsurface water (horizontally at the surface): taken by trawl net and 330 μm meshes</td>
<td>Micro-FTIR</td>
<td>0.33 ± 0.34</td>
<td>330</td>
<td>Zhang et al. (2017)</td>
</tr>
</tbody>
</table>

| Yellow Sea        | North Yellow Sea | Subsurface water (0.3 m depth): taken by Niskin hydrophore and 30 μm meshes | Micro-FTIR       | 545 ± 282                | 30             | Zhu et al. (2018)       |
| Bohai Sea         | North Bohai Sea  | Subsurface water (horizontally at the surface): taken by trawl net and 330 μm meshes | Micro-FTIR       | 0.33 ± 0.34              | 330            | Zhang et al. (2017)     |

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on the conclusions, so it is difficult to make an in-depth comparison of the different study regions. But this paper can still reach the following conclusions by preliminary analysis. (1) Microplastics are more abundant in surface water than deep water. The conclusion is consistent with fishing, sewage and industry being the main sources of microplastics in seawater, and that microplastics sink to the deep sea by biofouling (Li et al. 2016). (2) The abundance in estuaries is higher than in the sea, and urban pollution intensity has a positive correlation with the microplastics pollution levels of the surrounding water (Wright et al. 2013; Yonkos et al. 2017).

**Microplastics in sediments**

Studies on microplastics in sediments are shown in Table 2, and the units have been adjusted to be consistent for intuitive analysis. Microplastics abundance in the sediments of the South China Sea is higher than in the other three seas around China, and the abundance on beaches is higher than the abundance in deep sediments.

Compared to seawater, there has not been enough research on microplastics in the sediments of the seas around China, and the research methods have significant differences. In order to reach more objective conclusions, more research and consistent research methods are needed.

### Table 2 | Microplastics abundance in sediment

<table>
<thead>
<tr>
<th>Location</th>
<th>Regions</th>
<th>Sampling</th>
<th>Detection</th>
<th>Abundance (items/kg dry weight)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>South China Sea</td>
<td>Shapanwan</td>
<td>All sands were transferred into prepared aluminum foil bags.</td>
<td>Microscopy</td>
<td>Shapanwan: 5,014</td>
<td>Qiu et al. (2015)</td>
</tr>
<tr>
<td></td>
<td>Haikou</td>
<td>200 g sands were taken into a glass beaker to dry at 50°C to a constant weight</td>
<td></td>
<td>Haikou: 7,934</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wanning</td>
<td></td>
<td></td>
<td>Wanning: 871</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sanya</td>
<td></td>
<td></td>
<td>Sanya: 5,872</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Beihai</td>
<td></td>
<td></td>
<td>Beihai: 6,080</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hong Kong coastline</td>
<td>Collect the surface sediment samples (around 3 kg) by using an Ekman dredge</td>
<td>FTIR</td>
<td>49 ~ 279</td>
<td>Tsang et al. (2017)</td>
</tr>
<tr>
<td>East China Sea</td>
<td>Changjiang Estuary</td>
<td>Samples were collected with pre-cleaned bottles and taken from the upper 5–10 cm of the sea floor</td>
<td>Micro-FTIR</td>
<td>121 ± 9</td>
<td>Peng et al. (2017a)</td>
</tr>
<tr>
<td>Yellow Sea</td>
<td>North Yellow Sea</td>
<td>Sample gathered with a 0.1 m² Gray-O’Hara box corer from the topmost 5 cm of sediments (500–1,000 g)</td>
<td>Micro-FTIR</td>
<td>7.1 ± 42.7</td>
<td>Zhu et al. (2018)</td>
</tr>
<tr>
<td></td>
<td>North Yellow Sea</td>
<td>The depths of sampling sites ranged from 12 to 78 m.</td>
<td></td>
<td>123.6</td>
<td>Zhao et al. (2018)</td>
</tr>
<tr>
<td></td>
<td>South Yellow Sea</td>
<td>The sediments were sampled using a stainless steel box sampler</td>
<td></td>
<td>72</td>
<td></td>
</tr>
<tr>
<td>Bohai Sea</td>
<td></td>
<td>The depths of sampling sites ranged from 12 to 78 m.</td>
<td>Micro-FTIR</td>
<td>171.8</td>
<td>Zhao et al. (2018)</td>
</tr>
</tbody>
</table>

**Microplastics in marine species**

Sun et al. (2017) used nets of 505 μm mesh size (Nets I) and nets of 160 μm mesh size (Nets II) for the study of microplastics ingested by zooplankton groups in the northern South China Sea. The average abundance of microplastics was 4.1 pieces/m³ for Nets I and 131.5 pieces/m³ for Nets II, while the characteristics of the microplastics in Nets I and Nets II were similar. Microplastics were detected in all 21 species of marine fish that were collected from the Yangtze estuary, the East China Sea and the South China Sea, and 95.7% of the six freshwater fish species in Taihu Lake (Jabeen et al. 2017).

Sun et al. (2018) focused on the zooplankton groups in the East China Sea due to zooplankton’s sensitivity to microplastics, and 19 types of polymers were detected in the zooplankton groups. The bioaccumulated concentration of microplastics ranged from 0.13 ± 0.16 to 0.35 ± 0.18 pieces/zooplankton.

Qu et al. (2018) investigated the microplastics in mussels along the coastal waters of China; the sample sites covered 80% of the total length of mainland China’s coastline. The abundance of microplastics in mussels ranged from 1.52 to 5.36 items/g (wet weight) and from 0.77 to 8.22 items/individual. It showed a positive linear correlation between the microplastics in mussels and the microplastics in the
surrounding waters. And mussels were more likely to ingest smaller microplastics.

Although the studies are preliminary and not comprehensive, they can confirm that microplastics are ingested by a variety of marine species (Boerger et al. 2010; Cole et al. 2015; Lusher et al. 2013; Lonnstedt & Eklov 2016) and accumulate in the food chain (Vandermeersch et al. 2015). It can be concluded that biological interactions are very important to microplastics transformation and impact the fate of microplastics in the marine environment (Clark et al. 2016). So continuous observation of the food chain in the marine environment is an important direction for future research on the microplastics in the ocean around China.

THE CHARACTERISTICS OF MICROPLASTICS IN CHINA’S WATER ECOSYSTEMS

Size of microplastics

More than 70% of microplastics in the North Yellow Sea (both in surface seawater and sediments) were <1 mm according to Zhu et al. (2018), which is consistent with previous results that large plastics fragment into smaller pieces in the marine environments through mechanical effects, photooxidation and biodegradation (Gewert et al. 2013). The study is also consistent with the conclusion that fragments <500 μm were the most frequently observed size of microplastics in the Bohai Sea and the Yellow Sea (Zhao et al. 2018).

The size of microplastics ranged from 0.04 to 5 mm and accounted for 36.8–92.3% of the total plastics in each specific species (Jabeen et al. 2017).

Shape of microplastics

There was a prominent difference between the proportion of fibers in the Bohai Sea (Zhang et al. 2017) and the Yangtze River estuary (Zhao et al. 2014). The fibers accounted for 83% of the total plastics in the Yangtze River estuary but only 3% in the Bohai Sea. It can be concluded that the sampling sites were the main reason for the difference, as a previous study showed that fibers tended to sink to the bottom of the sea or remain suspended in the water column in the near-shore region (Engler 2012). The sampling sites in Zhang et al. (2017) were approximately 20 km away from the land, so only a few fibers were detected.

Zhur et al. (2018) showed that films and fibers (linear pieces of plastic were classified as fibers) were the dominant types of microplastics in the North Yellow Sea, accounting for 58.1 ± 24.9 and 39.1 ± 22.3% of the total microplastics. They were also the main types in the sediment of the North Yellow Sea, with proportion of 61.4 ± 14.2 and 35.1 ± 11.6, respectively. According to previous studies, the large number of films and fibers were caused by the wide use of plastic film in agriculture, the fragmentation of plastic bags and domestic sewage near the North Yellow Sea.

Four types of microplastics were observed in the sediments of the Bohai Sea and the Yellow Sea: fibers, fragments, films and pellets. Fibers accounted for 93.88% of the microplastics (Zhao et al. 2018), because of the high content of fibers in sewage, and fibers cannot be completely removed through sewage treatment (Browne et al. 2011).

Color of microplastics

Transparent plastic, colored plastic, white plastic and black plastic accounted for 58.9, 26.1, 8.7 and 6.2% in the surface water of the Yangtze Estuary. Transparent (28.8%) and colored (57.9%) plastic were also the main types of plastics in the surface water of the East China Sea (Zhao et al. 2014).

White plastic, transparent plastic, green plastic, yellow plastic and other colored plastic accounted for 68, 11, 10, 6, 5%, respectively, in the surface waters of the Bohai Sea (Zhang et al. 2017). The study also found that some white plastics turned pale yellow by weathering in the aquatic environment. In the study of Changjiang Estuary, the percentage of colored plastic (including blue, pink and gray) was 76.7%, and black and transparent plastic accounted for 18.2 and 5.1%, respectively (Xu et al. 2018). The proportion of colored plastic was different due to the source of microplastics. Transparent and colored microplastics are commonly used in plastic products, such as packaging, clothing and fishing line (Cole et al. 2015).

Some fish may mistake similar-looking microplastics, such as white, brown and yellow plastic, as food (Boerger et al. 2010). Jabeen et al. (2017) found nine colors of plastics in sea fish and six colors in freshwater fish, but the major colors were transparent, followed by black and blue.

Category of microplastics

Tsang et al. (2017) reported on the type and proportion of microplastics: they found polypropylene (50.9%), high-density polyethylene (26.4%), low-density polyethylene...
(18.2%), a blend of polypropylene and ethylene propylene (3.6%) and styrene acrylonitrile (0.9%) in the marine waters and sediments of Hong Kong.

In the surface water of the Bohai Sea, the main categories of microplastics were polyethylene, polypropylene, polystyrene and polyethylene terephthalate, accounting for 51, 29, 16 and 5%, respectively. Polypropylene was easily broken down into smaller particles in the marine environment and difficult to detect, so the proportion of polypropylene decreased with decreasing size. However, the proportion of polyethylene increased with decreasing size due to its higher impact strength (Zhang et al. 2017). This may be the main reason that previous studies found more polyethylene than polypropylene in the ocean.

Polyethylene, polypropylene and polyethylene/ethyl acrylate copolymer were the main components of microplastics in the North Yellow Sea, accounting for 77.8, 11.1 and 11.1% in the surface seawater and 44.5, 33.3, 11.1% in the sediments, respectively (Zhu 2011). The results are consistent with the wide applications of plastics in agricultural sediments, respectively (Zhu 2011). The microplastics in the North Yellow Sea, accounting for 77.8, 11.1 and 11.1% in the surface seawater and 44.5, 33.3, 11.1% in the sediments, respectively (Zhu 2011). The results are consistent with the wide applications of plastics in agricultural sediments, respectively (Zhu 2011).

Cai et al. (2018) found that polyester, polyethylene and polypropylene-polyethylene copolymers were the main components of large microplastics (0.3–5 mm), and the composition of small microplastics (0.02–0.5 mm) was alkyd resin (22.5%), polycaprolactone (20.9%), poly ethyl acrylate (15.5%), polystyrene (14.7%), polyurethane rubber (4.7%), polypropylene-polyethylene copolymer (3.8%), polyester terephthalic acid (3.8%) and other polymers (14%) in the South China Sea. The results are consistent with the common types of plastics in this area.

Zhao et al. (2018) found that the main source of microplastics pollution was textiles/clothing in the sediments of the Bohai Sea and the Yellow Sea. Rayon, polyethylene, polyethylene terephthalate, polypropylene and polyamide, accounted for 61.24, 16.29, 12.36, 7.30 and 2.81%, respectively, and they commonly came from the textile industry and laundering wastewater (Park et al. 2004; Browne et al. 2011).

THE FATE OF MICROPLASTICS IN WATER ECOSYSTEMS

Peng et al. (2017b) reported that the deep sea might be a sink for microplastics in the ocean, that the degradation of plastics would not only result in micro-fragmentation but that nano-fragmentation and organisms also played an important role in the fate of microplastics. Previous studies have shown the positive relationship between microplastics in hydrobios and microplastics in water (Browne et al. 2008; Andrady 2011; Claessens et al. 2011). Absorption and excretion of the mussels increased with the abundance of microplastics in water, and the amount of microplastics varied within a stable range (Li et al. 2016). Furthermore, the characteristics of microplastics in mussels were in accordance with those in the water (Qu et al. 2018), so mussels can be used as an indicator of microplastics in water. Based on previous studies, this paper summarizes the sources and transport routes of microplastics in the water ecosystem.

Source of microplastics

Microplastics enter the marine environment through sewage river flow, discharge, currents and wind, so land-based human activities are major sources of microplastics in the marine environment (Browne et al. 2010; Browne et al. 2011; Collignon et al. 2012; Auta et al. 2017). The microplastics mainly come from the plastic industry, including particles, debris, and additives from common daily items and polishing materials (Sun et al. 2017). Microplastics are also classified into primary microplastics and secondary microplastics according to the source (Moore 2008; Cole et al. 2011; Auta et al. 2017). Primary microplastics are products containing microplastics, such as synthetic fibers, cosmetics, medicine and raw materials; secondary microplastics are fragments released from larger plastics through mechanical action, biodegradation, photodegradation, photooxidative degradation and other processes (Rochman et al. 2013; Zbyszewski et al. 2014; Lechner & Ramlar 2015). Weathering and photodegradation are considered to be the most important processes for producing secondary microplastics (Arthur et al. 2009; Barnes et al. 2009).

Researchers found that the weather (wind, rainfall) was related to the distribution and abundance pattern of microplastics in water (Eerkes-Medrano et al. 2015). They also found that rainfall could intensify the plastics in the marine environment (Lattin et al. 2004), and that microplastics were more likely to accumulate in downwind sites (Browne et al. 2010; Moore et al. 2011).

According to the research on microplastic pollution, fibers are the most common shape in China’s water ecosystems, which is consistent with the findings that the first source of microplastics in the marine environment is sewage polluted with fibers from washing clothes (Oerlikon 2009; Browne et al. 2011). Although the efficiency of sewage
treatment system on microplastics can be up to 99%, the huge amount of microplastics will lead to serious pollution (Rochman et al. 2015), and the degree of microplastics pollution is related to population density.

Microplastics between the land and the ocean

Primary microplastics and secondary microplastics can enter the environment through wastewater, such as industrial accident spillages, the release of microbeads from cosmetics, and washing machines (Rocha-Santos & Duarte 2015). Previous studies showed that there were still a large amount of microplastics in wastewater after treatment (Talvitie et al. 2015; Carr et al. 2016; Murphy et al. 2016), so inland water systems might be an important pathway for microplastics to enter the water ecosystem (Cheung et al. 2016). Jambeck et al. (2015) estimated that 275 million tonnes of plastic waste were generated in 192 coastal countries in 2010, and 4.8 to 12.7 million tonnes entered the ocean.

The important role of inland water systems can be confirmed by correlation of the characteristics of inland water systems and marine systems (Zhang et al. 2018). Zhao et al. (2018) also found that the abundance of microplastics in sediments from the Bohai Sea was higher than from the Yellow Sea, and fibers were the most common type, which indicated that land-based input was an important source of marine microplastics.

When microplastics enter the ocean, the low-density microplastics can be carried by seawater and may also sink to the deep sea by biofouling; the high-density microplastics can be carried by the underlying currents (Engler 2012; Cózar et al. 2014). Kooi et al. (2017) predicted that the maximum concentration would appear in the intermediate depths of seawater due to biofouling. In addition, stranded plastic debris is likely to be transferred into seawater by increasing sea levels, altered rainfall, solar radiation, wind speed, waves and oceanic currents associated with climate change (Browne et al. 2015).

Microplastics in the food web

Microplastics can also be transmitted through the marine food web, as they are of a similar size to sediments and some planktonic organisms, so the feeding habits and living environment play important roles in the bioavailability of microplastics (Anastasopoulou et al. 2013; Desforges et al. 2015; Nadal et al. 2016). Bioaccumulation decreases from omnivores to carnivores and then herbivores in general (Gentleman et al. 2005; Mizraji et al. 2017). Bioaccumulation is more significant in zooplankton groups at the higher trophic levels (Sun et al. 2017), and fish can ingest high-density microplastics in their prey (Rummel et al. 2016). Microplastics can be transferred from the bottom of the water to the surface through ingestion by zooplankton groups (Clark et al. 2016), and the most common sizes of microplastics range from 20 to 300 μm in zooplankton groups in the East China Sea (Sun et al. 2018).

Qu et al. (2018) studied the coastal waters of China and reported the correlations of microplastics in mussels and surrounding waters in terms of abundance, size, shape and composition. This confirmed previous studies that fibers are the dominant shape both in marine species and seawater (Desforges et al. 2015; Kang et al. 2015; Mizraji et al. 2017). The conclusion that microplastics in fish are highly similar to the microplastics found in mussels along the coastline of China could also support those correlations (Li et al. 2016). So mussels might be the indicator organism for microplastics pollution in coastal waters (Li et al. 2015).

Jabeen et al. (2017) first reported the location of microplastics in fish around China, suggesting that their intestines absorbed more microplastics than their stomachs because of the coiled structure, consistent with the conclusion that bioaccumulation in intestines is higher than in other organs (Martínez-Gómez et al. 2017).

Microplastics in the sediments

Microplastics with a density greater than the seawater will sink down to the sediments, while microplastics with a density lower than the seawater will float on the surface. But the density of microplastics can grow through biofouling by organisms, so microplastics will eventually sink down to the sediments (Auta et al. 2017). Researchers have shown that deep sea areas, submarine canyons and marine coastal shallow sediments were the sinks for microplastics (Alomar et al. 2016). Researchers have detected microplastics in sediments from the Atlantic Ocean to the Mediterranean Sea, the Northwest Pacific Ocean and the Arctic Ocean (Van Cauwenberge et al. 2013; Fischer et al. 2015; Bergmann et al. 2017). Microplastics in sediments are mostly found in the surface sediments, with the abundance decreasing with increasing sediment depth (Willis et al. 2017).

Microplastics in the marine sediments can also get into the food web while benthic organisms feed on particulate matter (Nel et al. 2018). Zooplankton fecal pellets can affect the deposition of microplastics because of their low density (Cole et al. 2016). Bioturbation plays an important...
role in nutrient cycling, metabolism, dispersion and burial of marine pollutants, so the benthic organisms will affect the distribution of microplastics in sediments (Gebhardt & Forster 2018). By bioturbation, microplastics in sediments can sink to the bottom, move in other directions or back to the sediment–water interface. Besides bioturbation, microplastics can be resuspended by wind-driven waves, tidal streams and upwelling events (Nel et al. 2018).

THE RISK OF MICROPLASTICS IN WATER ECOSYSTEMS

Microplastics accumulation

Microplastics have been found in seawater, sediment and marine species. Microplastics can create new habitats for organisms (Majer et al. 2012), so biological activity will affect the dispersal of microplastics, even causing biological invasion (when organisms move from their original habitat to a new environment, where they may cause ecological damage) due to diffusion. Floating microplastics in seawater can influence the spread of sunlight and disturb normal life activities (Peng et al. 2017b). The characteristics and abundance of microplastics also affect nutrient bioavailability (Wright et al. 2013), but the mechanism between microplastics and biological performance still needs further study. Lei et al. (2018) found that microplastics could offer habitats to microbial communities and lead to the transformation or transduction of a pathogenic gene and an antibiotic resistance gene.

Entanglement often appears with microplastics accumulation, and the occurrence of plastic entanglement (55%) is much higher than plastic ingestion (31%) (Gall & Thompson 2015). Microplastics entanglement can cause direct and visible harm to animals. Entanglement of marine organisms, such as fish, seabirds, and mammals, can lead to drowning, suffocation, laceration, reduced fitness, a reduced ability to prey or an increased probability of being caught (Gilardi et al. 2010; Gall & Thompson 2015).

Microplastics chemical pollution

Besides organic pollutants added to microplastics in production in order to improve their properties (Bakir et al. 2014), microplastics can also absorb lots of pollutants because of the great specific surface area (Auta et al. 2017), and microplastics are particularly effective at carrying airborne pollutants because they are composed of highly hydrophobic materials (Ivar do Sul & Costa 2014). Researchers have found that microplastics contain pollutants, such as persistent organic pollutants (POPs) (Zarl & Matthies 2010), metals (Turner & Holmes 2013), and even nanoparticles, that can be adsorbed onto the surface of microplastics, including Fe, Al, Zn, Cu, Pb, TiO2 (Ashton et al. 2010; Fries et al. 2013) and endocrine-disrupting chemicals (Ng & Obbard 2006). Hydrophobicity, weathering and composition also affect the accumulation of pollutants (Hirai et al. 2011; Wang et al. 2016), so microplastics will be a dynamically contaminant carrier and pollute the marine environment. For example, polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated biphenyls can cause endocrine disruption in fish, and POPs can cause alterations in steroid hormones, thyroid hormones and prolactin in the glaucous gull (Verreault et al. 2006; Verboven et al. 2008).

Microplastics ingestion

Microplastics can be ingested by marine organisms and transmitted through the marine food web, and over 690 marine species at different trophic levels have been impacted by microplastics (Carbery et al. 2018). A comparison of the gut contents of fish on the Mediterranean Israeli coast showed that there was a temporal increase in the proportion of fish with microplastics, from 10% in 1960–1970 and 80% in the 1990s to 92% in 2016 (Van Der Hal et al. 2018). Jabeen et al. (2017) also reported that plastic pollution was widespread in the sea fish and freshwater fish of China.

Microplastics have been found in different tissues, such as gills, digestive glands, stomach and hepatopancreas (Farrell & Nelson 2015). Their ingestion can cause mechanical effects, such as the attachment of the polymer to external surfaces, hindering mobility, and clogging of the digestive tract; the effects can also be chemical, such as inflammation, hepatic stress and decreased growth (Setala et al. 2016). De Sa et al. (2018) reported the ecotoxicological effects of microplastics on different groups of organisms: for example, polyethylene microplastics can lead to neurotoxicity and the reduction of predatory performance.

THE REMOVAL OF MICROPLASTICS

Traditional WWTPs might be a significant source of microplastics because of the large volumes of effluents (Rochman et al. 2015), and the treatment technologies...
are not designed to remove microplastics (Mason et al. 2016). Advanced final-stage wastewater treatment technologies could improve the removal rate of microplastics (Mintenig et al. 2017; Park et al. 2017). Microplastics removal efficiency of WWTPs is above 88% with traditional treatment and above 97% with tertiary treatment (Sun et al. 2019).

**Traditional wastewater treatment plants**

Microplastics are mainly removed in primary treatment (50–98%) through solids skimming and sludge settling; secondary treatment can decrease the microplastics in the wastewater to 0.2–14% (Carr et al. 2016; Sun et al. 2019).

Pre-treatment is more effective for the removal of fibers than fragments, and the abundance of fibers decreases significantly after pre-treatment (Ziajahromi et al. 2017). Secondary treatment removes more fragments than fibers (Talvitie et al. 2015, 2016). Previous studies have shown the following removal efficiencies in traditional wastewater treatment plants: 98% removal of microplastics >250 μm (Lares et al. 2018), 99.9% removal of microplastics >100 μm (Carr et al. 2016), 98% removal of microplastics >65 μm (Murphy et al. 2016) and 99% removal of microplastics >10 μm (Simon et al. 2018).

Most microplastics are retained in the sewage sludge, and the average size of microplastics in sludge is larger than in the wastewater (Murphy et al. 2016). But there are no efficient and economical treatments for the microplastics in sewage sludge, although pyrolysis and co-pyrolysis with biomass might be the solutions for sewage sludge (Jin et al. 2019).

**Advanced tertiary treatment technologies**

Talvitie et al. (2017) reported that membrane bioreactor (MBR), disc filter, rapid sand filtration (RSF), dissolved air flotation (DAF) could substantially reduce microplastics (>20 μm) pollution (Table 3).

Sun et al. (2019) found that microplastics in wastewater would decrease to 0.2–2% after tertiary treatment. Adjusting the relevant operational parameters, such as the hydraulic retention time (HRT) or the pore sizes, is an economical way of improving the efficiency of microplastics removal. Flocculation/coagulation processes are potentially efficient technologies because Al-based coagulant and polyacrylamide could improve microplastics removal efficiency and have been confirmed in drinking water systems (Ma et al. 2019). But all the processes and technologies still need further study and field testing.

Lv et al. (2019) investigated the microplastics removal efficiency of oxidation ditch (OD) and MBR. The Orbal OD is L155 m × W74 m × H2 m with an average HRT of 15 hours, a solids retention time (SRT) of 10.0–12.0 days, and mixed liquid suspended solids (MLSS) of 3–5 g/L. The liquid–solid separation of the MBR is a submerged polyvinylidene fluoride (PVDF) hollow fiber membrane with a total effective membrane area of 12,720 m² and pore size of 0.1 μm. The A/A/O-MBR system operational parameters include an SRT of 20.5 days and MLSS of 8–12 g/L. The results showed that the microplastics removal efficiencies were 97% for the OD system and 99.5% for the MBR system on the basis of mass.

**CONCLUSION AND PERSPECTIVES**

The current conclusions can be summarized as follows:

(1) Microplastics are widely distributed in China’s water ecosystems, with fibers and polyethylene being their most common shape and composition. Microplastics pollution is more serious in estuaries, consistent with the conclusion that terrestrial activities seriously affect microplastics pollution.

(2) Research on microplastics has included seawater, sediments and organisms in China’s water ecosystems, but the research methods are not consistent. The mesh size, sampling depth, sampling tools and detection methods will affect the research results.
(3) Effluent from sewage treatment plants still contains large amounts of microplastics, and tertiary treatment technology could be the solution to improve the microplastics removal efficiency. In current sewage treatment plants, MBR is an efficient technology for microplastics.

The following suggestions should be addressed in future studies:

(1) Continuous monitoring of microplastics in water ecosystems needs to be conducted, to characterize the transmission and transformation of microplastics.

(2) The determination and promotion of a standard study method for microplastics is very important for the comparative analysis of data worldwide.

(3) Laboratory research to explore the mechanism of microplastic transformation to help remove the microplastics.

(4) Focus on the development of practical and efficient microplastics treatment technologies to help reduce the amount of microplastics entering the environment.

ACKNOWLEDGEMENTS

The work presented in this paper was supported by the technology research and engineering demonstration of water environmental pollution treatment in China’s Liaohe River (20200503003SF).

DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories.

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First received 18 May 2020; accepted in revised form 25 August 2020. Available online 7 September 2020