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Environmental fate and impacts of microplastics in aquatic ecosystems: a review

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Wide usage of plastic products leads to the global occurrence of microplastics (MPs) in the aquatic environment. Due to the small size, they can be bio-ingested, which may cause certain health effects. The present review starts with summarizing the main sources of various types of MPs and their occurrences in the aquatic environment, as well as their transportation and degradation pathways. The analysis of migration of MPs in water environments shows that the ultimate fate of most MPs in water environments is cracked into small fragments and sinking into the bottom of the ocean. The advantages and disadvantages of existing methods for detection and analysis of MPs are summarized. In addition, based on recent researches, the present review discusses MPs as carriers of organic pollutants and microorganisms, and explores the specific effects of MPs on aquatic organisms in the case of single and combined pollutants. Finally, by analysing the causes and influencing factors of their trophic transfer, the impact of MPs on high-level trophic organisms is explored.

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1. Introduction

Plastic products are widely used in many fields such as packaging materials (39.5% of total plastic output), building materials (20.1%), automotive parts (8.6%), electrical appliances (5.7%) and agricultural materials (3.4%), and the rest including household appliances, sports equipments, and other products.[1] Since the 1950s, plastics have been produced on a large scale.[2] In 2013, the global output of plastics had already reached 300 million tons and it is estimated that plastics production will increase to 33 billion tons by 2050.[3] There are various materials of plastics, such as polyethylene terephthalate (PET), polystyrene (PS), polyvinyl chloride (PVC), polypropylene (PP), polyethylene (PE), poly amide (PA), polyethylene terephthalate (PET), low density polyethylene (LDPE), polymethyl methacrylate (PMMA) and others.[4]

The ineffectively disposed plastic garbage in daily life has been entering the aquatic environment, and migrating with the hydrodynamic process over a long distance, which results in worldwide pollution.[2] In the marine environment, plastic accounts for about 60–80% of marine garbage.[5] To reduce the plastic pollution, a large number of studies have been carried out to reuse plastics. For example, researchers have explored the use of waste PET plastic bottles to make an innovative nonwoven packing material for wastewater treatment plants, and found that PET spunbonded nonwovens can be used as cost-effective, reliable and efficient packing materials for wastewater treatment.[6,7]

Microplastics (MPs) are generally defined as plastic particles with effective diameter less than 5 mm, and there is generally no specific lower size limitation.[8,9] They are distributed all over the world, from the mainland to the ocean, from cities to remote areas. Their sources can be divided into two main categories. One is specially manufactured in the micron size range, which can be called primary plastic particles, such as industrial abrasives (acrylic acid or polyester beads), plastic beads added into toothpaste and cosmetics, *etc.*[10,11] The other is plastic particles or fragments which are split or decomposed from large plastics in the environment, which can be called secondary plastic particles.[12]

Because of their small size, MPs are difficult to be identified in water. The detection and analysis of MPs is always done by visual inspection followed by Fourier-transform infrared spectroscopy (FTIR), Raman spectroscopy, and pyrolysis gas chromatography mass spectrometry (Pyro GC-MS), and so on.[13,14] The large specific surface area leads to the absorption of organic matters, which can act as a medium for pollutants to enter the aquatic food webs. Moreover, when plastic additives carried in MPs are released into the aquatic environment, harm to aquatic organisms could be caused.[15,16]

The present review is characterized by a more comprehensive introduction to the pollution, migration and biological effects of MPs in aquatic ecosystem. It emphasizes the influence of MPs on organisms in aquatic environment, which is analysed from the perspectives of MPs as carriers and transferring

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through trophic level respectively, and the role of chemistry is also discussed. The pollution situation and transportation of MPs in aquatic systems around the world are summarized. At the same time, degradation and fate of MPs in the aquatic environment are clarified. The existing detection and analysis methods of MPs, and the challenges in this field are also discussed. Suggestions are proposed for future research works in the end of the present review.

2. Occurrence and fate of MPs in the aquatic environment

2.1. MPs in the aquatic environment

2.1.1. MPs in the freshwater system. MPs pollution in freshwater is highly related to the terrestrial environment, when rivers flow through cities and towns, into which wastewater from plastic-related factories and other sewage discharges.[17]. It has been found that there is a positive correlation between the plastic load in the river and the amount of plastic wastes produced in the upstream watershed.[18,19] Urban areas can be seen as one source of plastic emissions.[20] For example, there are many plastic wastes in the Danube River, which contain about 79% of industrial raw materials discharged from urban areas.[21] In urban areas, discharge paths, such as wastewater discharge,[22] wastewater overflow, rainwater discharge, and littering could cause plastic pollution of rivers.[23,24]

Another important terrestrial source is farmland. The fertilizer,[25] plastic film or plastic greenhouse for heat preservation of crops,[26] and agricultural irrigation leads to the existence of a large number of MPs in agricultural soil.[27] They can migrate into the surrounding rivers and surface water through the rain and irrigation runoff of farmland. Firstly, synthetic fibers or deposited MPs in sewage sludge have been identified by many studies that MPs have been used as fertilizer or repair material.[28] So large amount of plastics enter into the terrestrial environment. After that, they enter the freshwater environment through rainfall or infiltration of the land. In European Union (EU), 4 to 5 million tons of sewage sludge are used annually for cultivating land.[29] Secondly, the extensively used mulch film in agriculture (especially in facility agriculture) is also an origin of plastic pollution in terrestrial environment.[30] However, the recovery rate of agricultural film is low, and a large amount of agricultural film remains in the environment after use.[31] Finally, the wastewater containing MPs was directly used for agriculture irrigation, resulting in the accumulation of MPs in the soil, and then migrating into the freshwater bodies. The type of MPs is one factor influencing the migration in soils, since microbeads and microfibers show different interaction with soil, which may affect the transportation of MPs in soil.[32]

Atmospheric deposition is also confirmed as a source of MPs in freshwater environment. For example, Dris *et al.* investigated atmospheric dust in Paris urban areas, and found that it contained man-made fibers.[33] Studies have shown that MPs in atmospheric environment can be transferred to water environment through transportation and sedimentation.[34] At the same time, sewage treatment plant is also one of the sources that can not be ignored, even it can remove part of MPs.[35] Generally speaking, the removal rate of MPs from wastewater in sewage treatment plants can reach 72%, most of which go to sewage sludge.[35] Many of the sludge from the sewage treatment plants are used to make crop fertilizer or directly applied, which make them as one major source of MPs into the ecological environment.[35]

Researches on the occurrence, accumulation, environmental effects, and methods of detecting plastics in freshwater have been carried out in recent decades, which showed that more attention has been paid to the existence of MPs in freshwater.[36] Table 1 shows the MPs particles detected in different freshwater environments around the world.[37] The detected MPs show different shapes, sizes and colours. At the same time, they have various chemical compositions and may carry other pollutants.[38]

2.1.2. MPs in the marine system. MPs are distributed in sea surface, water column, sediments[39] and marine organisms.[40] They can also be found at even far away from pollution sources, such as Polar Regions.[39] The pollution of MPs in marine surface water around world is shown in Table 2. The concentration of MPs in the marine surface water varies. Generally, the concentration of MPs in the surface water is higher along the coastal cities with higher degree of industrialization or the estuary of river.[41]

For water column, previous studies have shown that the abundance of MPs in water column is lower than that in surface water.[42,43] The MPs suspended in the water column are settling slowly every day, the number of MPs detected in the vertical distribution of deep seabed is four times of that in the surface layer.[44] So, the MPs in the water column tend to sink to the bottom. The water column distribution of MPs in the ocean is mainly horizontal or vertical. The main reasons for the horizontal migration of MPs are tidal ocean current and wind drive.[45] The results show that the areas with serious accumulation of MPs in the ocean basically coincide with the ocean current, so the ocean current plays a significant role in the horizontal transportation of MPs in the ocean.[46] For the vertical level, the main factor affecting the distribution in the water column is the density of MPs.[47] Generally, MPs made from materials with density greater than that of water are more likely to sink into the water column.[47]

For sediments, the amount of MPs in the sediment varies with geographical location. In terms of vertical distribution, the investigation results showed that the number concentration of plastic particles in coastal sediments ranges from 0.21 to 77 000 items per m^2, which is higher than those in deep-sea sediments.[48] In terms of the horizontal distribution, the concentrations of MPs are lower in remote areas. In the Yellow Sea and Xiangshan Bay of China, the concentration of MPs in sediments was 37.1 items per kg and 1739 items per kg, respectively.[49,50] In the Balearic Islands of Spain, the sediment contains around 106 items per km^2 of MPs.[51] In the Northwest Pacific Ocean, sediments are rich in MPs of 1.0×10^4 items per km^2.[52] In the remote Atlantic, the average concentration of MPs in the sediments was 1.15 items per m^3.[53]

For organisms, such as zooplankton,[54] mussels,[55] fish,[56] *etc.*, it is easy to intake MPs, which pose a risk to their life and bring MPs to somewhere else. The intake of MPs and distribution in organisms will be elucidated in the following Section 2.2.

Table 1 The concentration and pollution of MPs in freshwater system around the world

Region	Concentration	Shape	Type	Reference
North shore channel (North America)	1.94–17.93 items per m^3	Fragments Pellets Fibers	PS	158
Garda Lake (Italy)	1108 ± 983 items per m^2	Debris	PS PE PP PA PVC	159
Danube River (Europe)	316.8 ± 4664.6 items per m^3	Pellets Flakes Spherules Fragments	—	22
Antuã River (Portugal)	58–1265 items per m^3	Fibers Fragments	PE PP	160
Hovsgol Lake (Mongolian)	20 264 items per km^2	Fragments Films Pellets	—	161
St. Lawrence River (North America)	13 832 ± 13 677 items per m^2	Micro-beads	PE	162
Jiao Jiang (China)	960 items per m^3	—	—	117
San Gabriel River (California)	0–153 items per m^3	Fragments	PS	163
Ou Jiang (China)	680 items per m^3	—	—	117
Nakdong River (South Korea)	83–5242 items per m^3	Fibers	PP	164
Min Jiang (China)	1300 items per m^3	—	—	117
Raritan River (North America)	7.7–24 items/m^3	Fragments Films	—	165
Ulansuhai Lake (China)	1760–10 120 n per m^3	Fibers	PE PS PBT	166
Winnipeg Lake (Canada)	193 420–115567 items per km^2	Fibers	—	165
Taihu Lake (China)	3.4–25.8 items per L	Fibers	—	167
Saigon River (Vietnam)	10–223 items per m^3	Fragments Films	—	168
Tibet Plateau Lake (China)	563 ± 1219 items per m^2	—	PS PP PE PET PVC	169
Seine River (France)	0.28–47 items per m^3	Fibers Particles	PP PE PS	170
Three Gorges reservoir (China)	1597–12 611 n per m^3	Fibers Particles	PS PP PE	171

The influence of ocean currents on the distribution of MPs includes the movement of ocean currents, the drive of wind and other factors. Some factors also affect the migration of MPs when affecting the distribution of MPs, which will be explained in detail in the migration of MPs in the following Section 2.2.

The sources of MPs in marine environment include land-based input, shipping, marine aquaculture and fishing.[57] Firstly, as land-based waste, in many countries plastic garbages are dumped directly into the marine environment. Oztekin *et al.* investigated the marine garbage of Sarikum lagoon coast, and found that the garbages on the beach mainly came from 25 neighbouring countries, the most common type of garbages was plastic, accounting for 95.61%.[58] Secondly, the dumping from coastal cruise ships and merchant ships is another source for marine plastic pollution. In 2005, the United Nations Environment Program (UNEP) estimated that the amount of plastic wastes dumped into the sea by ships alone was as high as 5 million tons across the globe.[59] Thirdly, due to the development of aquaculture, fishing boats use more affordable plastic fishing nets to catch fish. When the old fishing products are replaced, the outdated fishing gears have not been properly disposed and then intentionally or unintentionally scattered in the ocean. According to U.S. official statistics, about 30 million pounds of plastic fishing gear pollution come from all over the world each year.[60]

2.2. Migration of MPs in aquatic systems

Most of the MPs in freshwater will eventually gather in the ocean, and further migration will take place.[61] The high concentration of MPs in the sea area is close to the

Table 2 The concentration and pollution of MPs in global marine surface waters

Location	Range of MPs concentration	MPs type	Reference
Arabian Bay	4.4×10^4 to 1.5×10^6 items per km^2	LDPE PP PET	172
South Pacific Ocean	0–4.0×10^5 items per km^2	—	173
East Asian seas around Japan	1.7×10^6 items per km^2	—	174
Western North Atlantic Ocean	0–5.8×10^5 items per km^2	PS	175
Mediterranean	0–9.0×10^5 items per km^2	PE	176
Northwestern Pacific	6.4×10^2 to 4.2×10^4 items per km^2	PE PP PA PVC PS	177
Mid-West Pacific Ocean	0.6–9.5×10^4 items per km^2	PP PE PET PMMA	178
Chesapeake Bay	0.007–1.25×10^3 items per km^2	PE PP	176
East China seacoasts	0.167 items per m^3	—	179
North Western Mediterranean Sea	0.12 items per m^2	PS	176
Northeast Pacific Ocean	1710 n per m^3	—	179
Southern coast of Korea	23 n per L	PA PS	180
Bohai Sea of China	0.22–0.53 items per m^3	PE PET	181
Yellow Sea of China	0.05–0.174 items per m^3	PE PET	182
East Sea of China	0.011–2.20 items per m^3	PE PP	183
Northeast Atlantic Ocean	2.46 items per m^3	—	184

industrialized cities.[62] For example, many MPs are found on the beach of Cartagena, an industrialized city near the Caribbean Sea.[62] The Mediterranean sea is surrounded by many industrialized and densely populated countries.[63] It is found that the concentration of MPs pollution in Iskenderun Bay and Mersin Bay, located on the north east coast of Levantine, Turkey, could reach up to 906 items per m^2.[63] Moreover, the increase of population density leads to the concentration increase of MPs from inland to estuary, and finally into the ocean.[64] The U.S. Environmental Protection Agency have shown that the link between marine pollution and rivers is clear.[65] Rivers act as a transport route, transporting MPs to the ocean. Sadri *et al.* surveyed the flow of MPs in Tamar River in England, found that the amount of MPs entering the estuary was consistent with the amount of MPs flowing out of the estuary.[66] Thus, it can be speculated that estuaries that receive MPs input from highly industrialized or densely populated catchment areas may contribute more to the ocean.[67] The migration of MPs in aquatic system can be divided into horizontal movement and vertical movement, which is closely related to the flow velocity, depth, flow change, bottom topography of water,[67,68] wind speed, and particle density.[69]

For the horizontal transportation, as the main transportation mode of MPs, the ocean current movement contributes greatly to the migration, distribution and concentration of MPs in the open ocean. The Spanish Marine Science and Technology Research Team found that the five major plastics pollution areas in the world's marine areas roughly coincide with the five major circulation flow on the surface of the sea area.[70] In the subtropical circulation zone of the North Pacific, the number concentration of plastic particles from 0 mg L^{-1} increased to 0.116 mg L^{-1} and the mass concentration of plastics from 0 particles/m^3 increased to 0.086 items per m^3.[70] Research shows that the influence of ocean current on concentration, the total amount of plastic particles in the North Pacific subtropical eddy enrichment area increased by two orders of magnitude from 1980 to 2000.[71] Similarly, other researchers have found that the accumulative concentration of MPs in subtropical circulation is very high.[72] In addition, due to the low density, MPs floating with the water flow and finally arriving at the sea.[73] After the MPs are transported to different water spaces, the spatial distribution of MPs changes significantly, whose concentration changes in order of magnitude in different regions.[74]

For the vertical transportation, density or buoyancy and the adsorption of MPs results in "dirt" on the surface, which increase the weight of MPs and leads them to sink.[75] During the decline process, these "dirty" MPs return to the surface.[76] Similarly, when biofilm formed on MPs, the hydrophobicity will decrease and the particle density will change, thus affecting its distribution in water.[77] For the vertical transportation, the driving force of wind also plays an important role. Driven by the wind, the flow could be turbulent, which could transfer the MPs

from the surface to the bottom.[78] The sinking speed of MPs in water is related to the particle density, particle size, fluid density and their shape. And the MPs will be aged or biologically polluted after a long time in the environment, which leads to vary of their mass. All these factors will change the settlement behavior of MPs.[79] Wind will not only drive the MPs to sink, but also drive them to float up from the bottom. For example, when the turbulent flows generate storms, the MPs at the lower water layer will rise to middle water layer.[80] Also, the intake by aquatic organisms is also an important reason for affecting the vertical transportation of MPs.[80,81] The aquatic organisms can absorb or retain MPs *in vivo* with different time periods, then transport MPs to a large extent, some of which will enter the deep sea.[82]

2.3. Degradation and fate of MPs in aquatic environment

For MPs, there are many types of degradation, including biological degradation, physical degradation, and chemical degradation.[83] The microorganisms get involved in biological degradation, mainly including bacteria, mold (fungi) and algae.[83] Microorganisms degrade MPs through hydrolysis and enzyme catalysis.[83] Physical degradation includes photo-degradation, thermal degradation and mechanical degradation, while chemical degradation mainly includes hydrolysis degradation and thermal oxidation degradation (Fig. 1).[83]

There are many factors affecting the degradation rate of MPs. Firstly, it is the type of the MPs.[83] Different types of MPs have different crystallinity, biodegradability, surface properties, oxidation resistance and residual monomers, which lead to different degradation rates.[84] Secondly, the interaction between MPs (especially for the non-biodegradable MPs) and microorganisms results in the biofilm formation on the surface of MPs, which increases the difficulty of degradation.[61] When the degradation rate is reduced, MPs are more vulnerable to microbial adhesion and pollution. The biofilm on the surface of polluted microorganism, a protective layer is formed, which further reduces the degradation rate.[74] Thirdly, the complex environmental conditions can affect the degradation rate of MPs. Their degradation rate in pure water environment is higher than those in simulated sea water environment.[74] Easily exposed to sunlight, the MPs can be degraded by ultraviolet radiation even at the bottom, so that MPs are more easily degraded in shallow lakes with smaller area[85] Similarly, in the marine system, the breakage or degradation rate of MPs near the coastline or beach will be several orders of magnitude higher than those floating in water column and sinking in marine sediments.[101] In the freshwater system, some rivers and lakes with large area will produce strong waves, which will lead to the breakage of MPs.[48] However, compared with the ocean, there is a lack of frequent turbulence, ocean current or wave and other ocean current movements.[85] Thus, the aging, fragmentation or mineralization of MPs will not occur easily in freshwater.[85]

After entering the marine environment, the degradation of MPs includes size variation and mineralization. This means that the polymer chain of the MPs is further destroyed, and the molecular weight of the polymer is reduced.[86] Due to the needs of microorganisms' own growth, microbial colonies will convert organic matters from MPs into carbon dioxide and incorporated into biomass.[87] However, research shows that it takes hundreds of years for MPs to be fully mineralized.[86] Hence, MPs are

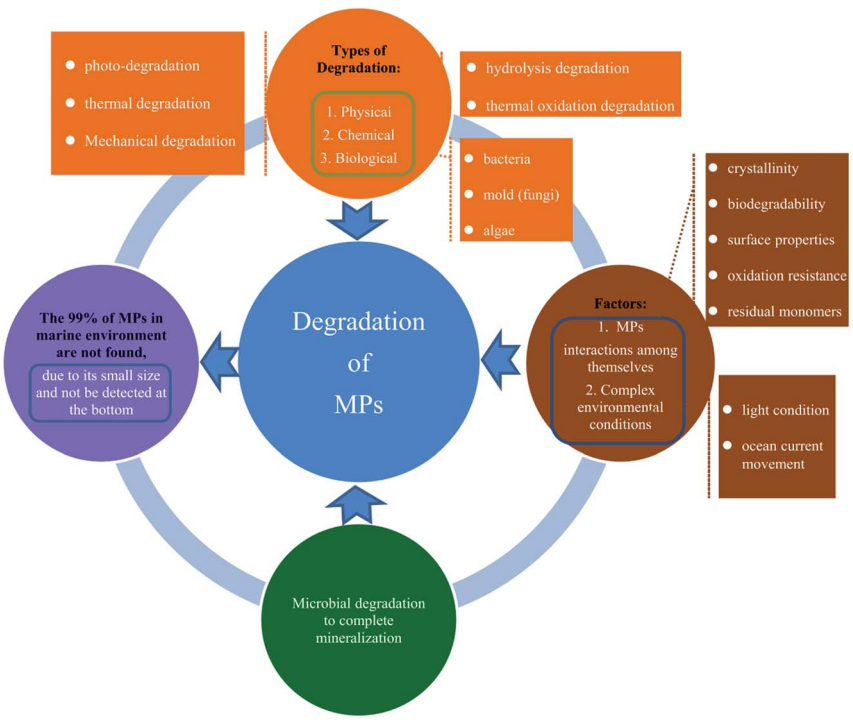

Fig. 1 Degradation of MPs in the aquatic environment.

considered to be relatively persistent in the aquatic environment, and the degradation of MPs are more likely to occur at the surface water, beach or coastline.[74]

After entering the aquatic environment, it is generally believed that the fate of MPs occurs in the ocean.[61] The fate of MPs in the marine system is affected by many environmental factors, such as the ocean current, food abundance of marine organisms and others.[88] In the ocean, it is found that 70–80% of MPs finally enter the sea bottom or exist in the seabed sediments.[61] The remaining stays in the coastal areas or the surface water respectively.[89] Now, the amount of MPs found in the ocean is only 1% of the amount that was dumped into the ocean theoretically. The remaining 99% of the MPs are not found because they are broken down into pieces that are too small to be found, or they are not detected on the bottom of the ocean, rather than disappearing.

2.4. Detection and analysis methods of MPs in the aquatic environment

The MPs fragments suspended in aquatic environment are generally collected by nets or trawls, then followed by sample preparation, usually including sample digestion and density separation.[90] At present, the quantitative and qualitative detection technologies for MPs include visual method, spectroscopic method, chromatographic method, and so on.[14] Visual inspection with the help of stereoscope or microscope for direct observation is commonly used.[28,91] However, this method is highly subjective, time-consuming, and easy to lead to some types and colors of MPs recognition errors due to experience and fatigue.[92] FTIR is well-established, fast, quite-reliable and non-destructive method, which can be used to analyze the molecules with polar functional groups such as carbonyl groups.[93,94] However, it is always limited to certain diffraction range, the size of MPs down to 20 μm can analyzed by coupling with microscopy.[95] Raman spectroscopy can offer structural information of MPs falling in the range of 1 to 20 μm.[96] However, the interferences of fluorescence from biological, organic and inorganic impurities can hamper the identification.[36] FTIR and Raman spectroscopy are complementary vibrational techniques, which can offer complementary information on MPs.

Thermoanalytical methods such as Pyro GC-MS and thermogravimetric analysis-mass spectrometry (TGA-MS) have been applied to MPs analysis, which are destructive methods. MPs at first are thermally degraded, and the products are subsequently sent to MS for analysis. And then the obtained data are compared with reference to get information.[36] They can offer sensitive and reliable information about the MPs and the organic plastic additives in one run, without the background interference from solvents,[97] which are considered as the best methods for the analysis of oil-based MPs.[98] However, they are suitable for the MPs with diameter larger than 500 μm, which can be manually handled.[36,99] At the same time, they are largely dependent on the reference database.[36,99] Other methods include X-ray fluorescence (XRF) spectrometer, Scanning electron microscope (SEM) and liquid chromatography mass spectrometry (LC-MS), whose advantages and limitations are shown in Table 3.[100]

However, there are still a lot of challenges in this field. For example, smaller size plastics, just like nanoplastics, are not easily to be collected and quantified, which leads to underestimation of their pollution. And the non-standardized analysis protocols lead to different explanation of MPs abundance.

3. Impacts of MPs in aquatic system

3.1. MPs as carriers in aquatic system

MPs have large specific surface area and good adsorption, which has been proved to be an important carrier for chemicals and microorganisms, which can pose great risk to aquatic biota, even to the ecosystem (Fig. 2).

3.1.1. MPs as carriers for pollutants. MPs have good hydrophobicity, and they are known to be vector of pollutants. In recent years, many studies about the interaction between MPs and other pollutants have been done. There are two main kinds of pollutants carried by MPs: one is monomer, additive and other by-products contained in MPs; another is some heavy metals and hydrophobic compounds from environment.[101,102]

MPs are made of monomers as raw material through addition polymerization or polycondensation reaction. The common monomers of plastics include acrylic and meth acrylic acid monomers, vinyl monomers, functional monomers (crosslinking monomers) and water-soluble monomers (surface active monomers). The common plastic additives are phthalates, aliphatic binary esters, and phosphate epoxy compounds. Among them, phthalate is the most common one.[103] Some other by-products are added according to different uses, such as dyes, pigments, *etc.*

The heavy metals commonly adsorbed by MPs are lead, zinc, copper, chromium, cadmium.[104] MPs are very easy to wear under natural conditions, and adsorb sediment, charged minerals and organisms, which leads to the adsorption of metal cations on the surface with charge.[105] Studies have shown that the pH value of water environment and the retention time of MPs in the environment are important factors affecting the adsorption capacity of MPs to metal ions.[106] MPs can also adsorb some hydrophobic persistent organic pollutants, such as polychlorinated biphenyls, polybrominated diphenyl ethers, organochlorine pesticides, polycyclic aromatic hydrocarbons, petroleum hydrocarbons, bisphenol A.[107] For organic chemicals, Wang *et al.* showed that organic chemicals could be easily adsorbed on MPs due to their hydrophobicity.[108] Polychlorinated biphenyls (PCBs) and 1-chloro-2-[2,2-dichloro-1-(4-chlorophenyl)ethenyl]benzene (DDE) were detected on polypropylene MPs collected in the sea near Japan,[109] whose highest concentrations are 117 ng g^{-1} and 3.1 ng g^{-1} respectively,[110] mainly coming from the water. In addition to the properties of the adsorbed chemicals, characteristics of MPs, the weathering/aging effect of plastics themselves, the pH and the ionic strength of water bodies can also affect the adsorption capacity.[111–114]

3.1.2. MPs as carriers for microorganisms (biofilm). The surface of MPs is hydrophobic so that some microorganisms

Table 3 Comparison of advantages and limitations of collection and detection methods of MPs

Methods		Advantages	Limitations	References
Visual method	Microscopic counting	Low cost, short detection time, can detect large sample size (>1 μm), detection shape is various (fibres, synthetic particles, fragments, textile fibres)	The nature of the sample cannot be determined and must be used in combination with other identification methods	14, 91 and 185
Spectroscopic methods	FTIR	Non-destructive testing technology, can quickly obtain thousands of spectra in a region, short analysis time, detection shape is various (fibres, fragments)	Expensive, needs to be operated and processed by special personnel. The detection process and data analysis will be affected by the environment. The detection size range is concentrated in 20 to 500 μm	14 and 186
	Raman Spectroscopy	1–20 μm small particles and opaque particles can be analyzed, automatic data acquisition and processing	Organic and inorganic impurities need to be removed before sample analysis, time-consuming	187 and 188
	Scanning Electron Spectroscopy	High resolution image can be obtained for sample analysis, various detection shape (synthetic particle, fibres)	Samples need to be coated in high vacuum for detection. Only large size can be detected (1–5 mm)	14
Thermo analytical methods	Pyro GC-MS TGA-MS	The samples can be analyzed with organic plastic additives without solvent pretreatment, detect synthetic particles and fibers with the size larger than 500 μm	Only the selected MPs in the database can be analyzed with thermo analytical methods, and certain requirements for the particle weight to be evaluated	14 and 189
	Thermogravimetric analysis is combined with the solid-phase extraction (TGA-SPE) Thermal desorption gas chromatography mass spectrometer (TDS-GC/MS)	TGA-SPE and TDS-GC/MS allow the direct MPs assessment from the field environmental samples with ease in sample preparation		
Other methods	Tagging method	The method is simple, easy to operate, can quickly screen out the required MPs and identify fluorescent particles	The evaluation of the abundance of MPs is not accurate, and it is on the high side. Only large size MPs samples (1–5 mm) can be detected	190
	Liquid chromatography	Recover high content of MPs.	The sample size of evaluation analysis is small, and only specific MPs can be analyzed	191 and 192
	SEM dispersive X-ray spectrometer	Provide high-resolution data of surface state and qualitative information about the chemical composition	It is time-consuming and expensive, chemical characterization may be subject to a selection bias	193

could easily settle on their surface, then a kind of biofilm called "plastic ring" was formed.[115] At present, the formation of plastic ring has been studied in marine environment, but it is not clear in freshwater environment.[116] In the freshwater system, the latest research has studied the biofilm on the surface of different kinds of MPs, such as PS, PET, PE, *etc.* It is found that the MPs in wastewater treatment plants can be used as carriers for microorganism attachment, and the content of biofilm is related to the properties (hydrophobicity, roughness) and living environment of MPs.[116] Generally, the rougher the surface and the stronger the hydrophobicity, the better the adhesion of microorganisms.[116] At the same time, it was found that there were many kinds of microorganisms attached to the MPs, such as antibiotic resistant bacteria and some pathogenic bacteria, which indicated that the MPs might be potential carriers of pathogenic bacteria.[116] The effluent of sewage treatment plant contains both MPs and antibiotics.[116] Therefore, MPs can

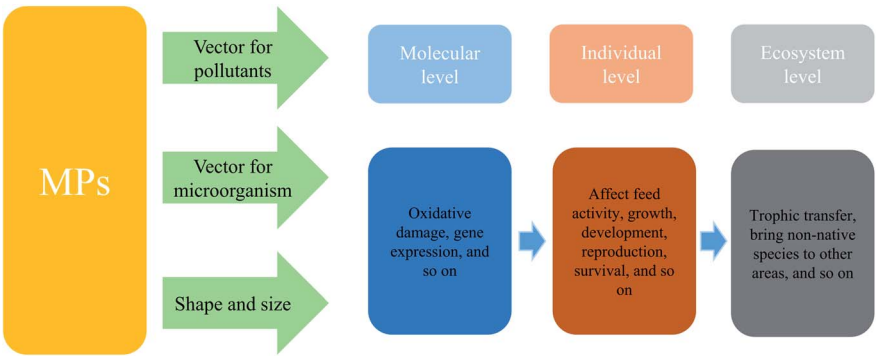

Fig. 2 Impacts of MPs on aquatic biota.

transmit resistance genes to rivers and oceans with the effluent of sewage treatment plants.[116]

In the marine environment, the adsorption of plastic particles starts shortly after invading into water, and a biofilm with stable adsorption can be produced in 7 days.[117] About 22% of the MPs particles have small algae and foraminifera on their surface in the French Gulf waters.[118] The investigation in the North Atlantic by Zettler *et al.* showed that the microbial communities adsorbed on plastic particles in coastal waters are heterotrophic, autotrophic or symbiotic.[119] The factors that influence this biological attachment are extremely complex, including seasonal changes, geographical location, water temperature, nutrient status of seawater, sediment type, and water flow velocity.[120]

3.2. Effects of MPs on aquatic biota

The influence of MPs on organisms can be divided into physical and chemical aspects, which is shown in Table 4. On the physical level, MPs debris can have a direct mechanical impact on aquatic organisms through entanglement and swallowing.[112] After swallowing, the debris will produce a false sense of satiety, thus affecting appetite, and even cause internal blockage or damage to the digestive system.[112] MPs aggregate in the digestive tract of organisms, and smaller particles even can enter and stay in the circulatory system.[121] The size affects the accumulation of MPs in the organism, then affecting the growth and reproduction of living organisms. Jeong *et al.* studied the aggregation effect and adverse effects of different sizes of MPs in rotifers.[122] The results showed that smaller size of MPs particles were more easily absorbed and accumulated by organisms, which reduced the growth rate, fecundity and longevity of organisms.[122] Other researchers have found that MPs can penetrate intestinal epithelium into biological tissue, thus causing greater harm to organisms.[123,124] MPs are not only vary in size but also in shape, such as spheres, fragments or fibers (shown in Table 4). The effects of MPs with different shapes are different in organisms. It is found that, among these shapes, fiber morphology was more toxic to adult *T. monodon*.[125] Studies have also confirmed that residual fibers are more likely to be entangled in the intestine, which ultimately leaded to the death of organisms, since fibers cannot be completely excreted, resulting in long retention in the body.[126] Jahan *et al.* found that fibrous MPs tend to accumulate in oysters, more than spherical or other shapes of MPs.[127] The easier retention and less excretion may result in damage to the gastrointestinal function of organisms or death due to blockage of the intestinal tract.[128]

MPs will transport the carried chemicals to organisms.[112] The chemicals absorbed by MPs, such as polychlorinated biphenyls, have carcinogenic, teratogenic and mutagenic effects on organisms.[112] Studies have found that MPs with pollutants could promote the accumulation of these pollutants in aquatic organisms.[129] Researches have shown that the chemical pollutants adsorbed on the MPs can be bioavailable, thus affecting molecular and cellular pathways, which are summarized in Table 4.

In order to meet the needs of production and usage, many chemical additives, such as plasticizers and dyes, are added into the manufacturing process. Generally, different plastics need different chemical polymers with different plastic additives. Common plastics additives include antioxidant, flame retardant and plasticizer.[130] These additives not only can be transferred to aquatic organisms through the intake of MPs by organism, but also can be released during plastics degradation to the aquatic environment. Plastic additives such as bisphenol A, octyl phenol, nonylphenol, brominated flame retardant, boric acid, tri(2-chloroethyl)phosphoric acid, *etc.*,[131] were found in nature waters. The specific effects of these additives and adsorbed chemical pollutants on organisms are shown in Table 4. Although MPs with pollutants could promote the accumulation of these pollutants in aquatic organisms, the toxic effects of the coexistence of MPs with pollutants on organisms are uncertain. Some studies have found that, although MPs can carry into the organism and promote the accumulation of these pollutants in aquatic organisms, the existence of MPs will not increase the impact of these pollutants on the organism.[132,133] For example, the coexistence of PS, PA, PE and some chemicals, such as bisphenol, peptides, dimethoate and deltamethrin does not change the 50% effective concentration of these chemicals to organisms.[134] For glyphosate and 17α-ethinylestradiol, the presence of MPs may reduce their toxicity.[134] For phenanthrene, the presence of MPs may increase it toxicity.[134] According to the different endpoint analyzed or treatment methods, the presence of MPs may also increase the toxicity of coexisting chemicals.[134]

Table 4 The effects of physical and chemical factors of MPs on aquatic biota

			MPs			
Cohort	Species	Contamination	Size	Shape	Type	Impact and mechanism
Algae	*Skeletonema costatum*	Cu	1 μm	Spherical powder	PVC	Copper inhibited the growth of the organism, but the adsorption of Cu^{2+} and the aggregation of copper nanoparticles and MPs reduced the toxicity of copper nanoparticles due to the presence of MPs[194]
	Chlorella pyrenoidosa	Triphenyltin chloride (TPTCI)	0.55 μm 5 μm	Beads	PS	PS exposure will lead to the destruction of algal cell structure, leading to the accelerated uptake of TPTCl by green algae, thus increasing the toxicity of TPTCl[195]
	Chlorella pyrenoidosa	Dibutyl phthalate (DBP)	0.1 μm 0.55 μm 5 μm	Beads	PE	The presence of MPs results in the decrease of bioavailability of DBP in microalgae, and the co-action of heteropolymerization and copolymerization leads to the antagonistic effect of DBP in MPs. This effect negatively affected the volume, morphological complexity and chlorophyll fluorescence intensity of microalgae cells[196]
	Phaeodactylum tricornutum	Phenanthrene (Phe)	150 μm 250 μm	Powder	PE PVC	The accumulation of lipid in algal fluid was induced by chronic toxic exposure, but the combined exposure of MPs and phenanthrene ether of different sizes had no effect on the growth of algal fluid, and even reduced the toxicity level of single exposure to some extent[197]
	Chlorella spp., *Scenedesmus* spp.	—	—	—	PS	The MPs particles block light and air, blocking photosynthesis in algae. At the same time, the presence of MPs leads to the increase of reactive oxygen species (ROS) in algae[198]
	Scenedesmus obliquus	—	<1 μm	Beads	Nano-PS	That chlorophyll content decreased and some effects on growth and photosynthesis appeared[199]
	Dunaliella tertiolecta *Thalassiosira pseudonana* *Chlorella vulgaris*	—	—	Beads	PS	The photosynthetic efficiency of *Dunaliella tertiolecta*, *Thalassiosira pseudonana*, and *Chlorella vulgaris* decreased significantly under the action of a certain range of PS particles[137]
	Chlamydomonas reinhardtii	—	—	Beads	PP HDPE	It can be concluded that the toxicity of MPs to algae generally increases with the decrease of the particle size[200]
Crustaceans	*Hyalella azteca*	—	—	—	PE PP	The mortality rate of *Hyalella azteca* increased with the increasing of the exposure dosage, showing a significant dose-effect relationship[138]
	Acartia tonsa *Calanus finmarchicus*	Polycyclic aromatic hydrocarbons (PAHs)	10–200 μm	Micro-beads	PS PE	Co-exposure to MPs and PAHs improved the bioavailability of free dissolved PAHs, and with the dissolution of MPs to PAHs adsorption, the lethal and bioaccumulation of organisms decreased[201]
	Alrchestes compressae	PBDE-28, -47, -99, -100, -153, -154, -183	11–700 μm	—	PE	Polybrominated diphenyl ethers (PBDE) can be absorbed into the tissues of organisms, but the presence of PS MPs reduces the uptake of PBDEs by organisms. At the same time, the biological uptake of the homologous substances of different PBDEs was different, and the uptake of PBDE-154 and -153 was higher than that of PBDE-28 and -47 [202]
	Tigriopus japonicus	—	—	—	PE PP	The fatality rate of *Tigriopus japonicus* also increased significantly with the increase of dosage[203]
	Daphnia magna		100 nm	—	PS	

Table 4 (*Contd.*)

Cohort	Species	Contamination	MPs			Impact and mechanism
			Size	Shape	Type	
		Polychlorinated biphenyls-18 (PCB)				As the concentration of PCB-18 decreased, co-existence of PCB-18 with low concentration of PS reduced the biological toxicity, but with the increase of PS concentration, the toxicity of PS was far greater than that of PCB-18, causing death of *Daphnia magna*[204]
	Daphnia magna	—	10 μm, 1 mm	Beads	PS	*Daphnia magna* can quickly ingest MPs of 0.01 and 1 mm, and accumulate them in fat droplets, which shows that MPs can destroy the filtration process of crustaceans.[205] The possible cause of death observed is only blockage in the intestine, not chemicals released from plastic fibers[139]
	Langoustine (*Nephrops norvegicus*) Clyde Sea Area	—	—	Fibres	PS	Crustaceans ingest MPs through passive ingestion of sediments or in-taking of prey contaminated with MPs.[206] Generally, female lobsters retain more MPs particles than male ones[206]
	Eriocheir sinensis	—	—	Fragment	—	For crabs, male crabs consume more MPs than female ones[207]
	Carcinus maenas	—	8 μm	Beads	PS	MPs intaken by crabs could significantly reduce oxygen consumption in hemolymph, decrease Na^+ concentration, increase Ca^{2+} concentration and hemocyanin content[208]
Bivalves and zooplankton	Blue Mussel *Mytilus edulis* L. *Granulocytoma*	—	0–80 μm	—	HDPE	The intake of MPs can lead to a significant decrease in lysosomal membrane stability and a significant increase in the number of *L. Granulocytomas*[209]
	Centropages typicus, *Calanus helgolandicus*	—	1.7–30.6 μm	Beads	PS	The feeding performance of *Centropages typicus* was significantly reduced after 7.3 μm MPs was ingested.[120,210] The intake, fecundity and survival rate of *Calanus helgolandicus* showed a downward trend after taking PS particles[120,210]
	Mytilus edudis	PCB-18 20, 28, 29, 31, 44, 52, 101, 105, 118, 138, 143, 149, 153, 155, 170, 180, 194, 204, and 209	400–1300 μm	Beads	PS	A positive relation was observed between PS concentration in the sediment and both uptake of plastic particles and weight loss. A low PS dose of 0.074% increased bioaccumulation of PCBs by a factor of 1−3 mm PS had statistically significant effects on the organisms' fitness and bioaccumulation[211]
	Mytilus eduli (L.)	—	2 μm and 6 μm, 30 μm	Beads	PS	The in-taken MPs in hemolymph and circulatory system of marine mussels can exert physiological pressure on organisms.[212] For example, when MPs enter into the hemolymph system, the mortality rate of blood cells would increase, leading to the formation of shell and wound healing.[213,214] Also, the number and size of oocytes and sperm activity rate was significantly reduced, when oysters were exposed to MPs.[215] MPs still cause a negative impact on the population and survival of bivalves[216]
	Mytilus spp.		3 μm and 9.6 μm			
	Arenicola marina	PBDE-47 Nonylphenol Phenanthrene Triclosan	230 μm	—	PVC	Intake of different chemicals from PVC has different effects on organisms. Intake of nonylphenol reduces the ability of biological cells to remove pathogenic bacteria, while intake of triclosan can lead to death in severe cases. Exposure to PVC alone causes organisms to be more susceptible to pathogenic stress[216]
	Mytilus galloprovincialis	Pyrene	100 μm	—	PS PE	Bioingestion of MPs may adversely affect the digestive tract, respiratory system and motor appendages[217]
	Mysid shrimps *Copepods* *Cladocerans*	—	—	Beads	PS	Zooplankton have the potential to absorb small plastics.[218] The uptake of MPs by zooplankton largely depends on the concentration, size of particles and their feeding mechanism[219]

Table 4 (*Contd.*)

Cohort	Species	Contamination	MPs			Impact and mechanism
			Size	Shape	Type	
	Rotifers polychaete larvae					
Vertebrate	*Danio rerio*	—	<1 μm	—	PE	The result showed that acute exposure may affect the aryl hydrocarbon receptor (AHR) pathway, interrupting the development of eggs and producing neurotoxic effects[220]
	Clarias gariepinus	Phenanthrene	<60 μm	—	LDPE	Exposure to both MPs and phenanthrene inhibits acetylcholinesterase activity and reduces the amount of energy produced by the aerobic pathway. The presence of MPs regulates the bioavailability or biotransformation of phenanthrene[221]
	Danio rerio	—	<1 μm	—	Nano-PS	Results showed that some nano-plastics can penetrate the intestinal of developing *Danio rerio* in polluted aquatic ecosystems, accumulate in tissues, and affect their physiology and behaviour[222]
	Danio rerio	Tetrabromobisphenol A (TBBPA)	100 μm	Beads	PE	Co-exposure induced significant antioxidative stress than either PE or TBBPA alone when exposed to MP[223]
	Stellifer brasiliensis *Stellifer stellifer*	—	1–5 mm	Nylon fragments	—	The amount of fish that ingested plastic accounted for 6.9% to 9.2% of the total amount of the fish depending on the different size of MPs.[224] Also, the Gerreidae consumed much more blue nylon fragments of 1–5 mm than other sizes[225]
	Pomatoschistus microps	Cefalexin	1–5 μm	Beads	PE	The presence of MPs can affect the toxicity of cefalexin, and the biological toxicity of both MPs and cefalexin either alone or in combination with MPs increases with the increase of temperature to *P. microps* juveniles[226]
	Danio rerio	—	5 nm, 70 nm	Beads	PS	MPs with different particle sizes can accumulate in gills, liver and intestines of *Danio rerio*.[227]
	Pomatoschistus microps	—	—	—	—	MPs produced a cumulative effect of reducing hepatic glycogen content and fat vacuole degeneration *in vivo*.[221]
	Pomatoschistus microps	Chromium	1–5 μm	Beads	PE	Exposure to low concentrations of Cr(VI) and MPs will not have toxic effects on organisms, but long-term exposure to natural habitats before biological development will affect the sensitivity and response to Cr(VI)[228]
	Dicentrarchus labrax	—	—	—	PE	The mortality rate of *Dicentrarchus labrax* increased by about 14% with the increase of exposure dose.[229] And for endocrine aspects, such as CYP 1α, vitellogenin I and estrogen receptor alpha expression in females and males, as well as the expression of chorionic protein H in males, there was no significant difference with control ones[221]
	Danio rerio	Bisphenol A Bisphenol S Octylphenol Nonylphenol	1–3 mm	Fragments	PE	Normal life stresses can decrease endocrine disrupting chemicals (EDC) concentrations, but solar irradiation (solar) can increase EDC concentrations in leachates.[230]
	Danio rerio	—	—	—	HDPE	The gene expression profiles of the phase 1 detoxification-related gene (cyp 1α) in the intestine and oogenesis-related gene (vtg 1) in the liver showed significant upregulation.[230]
	Danio rerio	—	4–12 μm	Beads	PE	

Table 4 (*Contd.*)

Cohort	Species	Contamination	MPs			Impact and mechanism
			Size	Shape	Type	
						Aging of MPs in low organic-load waters mitigated the toxicity of MPs for organism, while MPs aged in high-organic load waters had the same adverse effect as MPs[231]
	Danio rerio	—	—	—	PA, PP, PE PVC, PS	Intestinal cell division and GST increased, although there was no significant change in mortality and intestinal villus rupture[232]
	Pomatoschistus microps	—	1-5μm	Beads	PE	A large amount of MPs could be ingested, and the mortality rate was significantly increased after the ingestion[229]
	Dicentrarchus labrax	—	<1 mm	Beads, debris	PE	The intake of MPs also resulted in intestinal obstruction,[233] severe glycogen depletion, abnormal proliferation of testicular germ cells and other adverse effects such as liver stress[234]
	Clarias gariepinus *Dicentrarchus labrax*	Mercury	1-5μm	Micro-spheres	—	MPs influence the bioaccumulation of mercury. MPs, mercury and their mixtures cause neurotoxicity, oxidative stress and damage, and changes in the activities of energy related enzymes in juveniles of this species[235]
	Gammarus roeseli	—	50–500 μm	Fragment	LDPE	The transcription levels of forkhead box L2 (*foxl2*) and tryptophan hydroxylase 2 (*tph2*) *in vivo* were significantly reduced[236]
	Dicentrarchus labrax (Linnaeus, 1758)	Phenanthrene	—	—	PA	The exposure of gammarids in presence of either particle type with phenanthrene resulted after 24 and 48 h in reduced size[237]
	Dicentrarchus labrax	—	—	Pellets	PVC	Long-term exposure to MPs can lead to significant changes in intestinal structure and function. This may lead to serious damage to the fish development in the early stage, thus adversely affecting the reproductive success, population size and survival of fish[238]

Moreover, the different structure of the same MPs will also lead to different toxic effects on organisms. Studies have shown that the combined toxicity of Ni and PS MPs with –COOH functional group is higher than that of Ni and PS MPs without –COOH functional group.[135]

For organisms, the existence of MPs in water can exert effects on algae, crustaceans, bivalves, zooplankton and vertebrates in freshwater and marine organisms. For algae, the existence of MPs has a physical impact on the flow of light and air, and has an impact on the chlorophyll of algae.[136] All of these factors lead to a significant decrease in the photosynthetic efficiency of algae.[137] For crustaceans, the MPs have an impact on the normal life style. The mortality rate will increase with the increasing of the exposure dosage, showing a significant dose-effect relationship, due to the toxicity of MPs.[138] At the same time, the presence of MPs can lead to the death of crustaceans, which can lead to intestinal obstruction by destroying crustaceans' filtration systems.[139] Many large crustaceans are omnivores, which do not recognize and discard food-related plastic filaments. They can easily ingest large amounts of MPs. Studies have shown that free-swimming crustaceans consume more MPs than sessile ones.[140] The retention of in-taken MPs is related to gender, size and molting stage.[141] Moreover, the intake of MPs may lead to development retardation of crustacean, decreased fecundity and delayed molting.[142] For bivalves, they are self-sufficient compared with other marine invertebrates, because their preferential feeding mechanism allows them to reject non-food particles.[143] The bivalves also have other selection mechanisms, such as pre-feeding of lip flaps, gastric post-feeding selection, and so on.[143] The inadequate food sources and abundant MPs in biological habitats may be one of the reasons for them to ingest MPs. For vertebrate, there are two main ways for them to ingest MPs. One is to prey on organisms polluted by MPs; the other is to take MPs directly from water column and sediment.

Fish's feeding behavior affects the size and quantity of MPs they consume. Omniphagous consume more MPs than single herbivorous or meat-eating fish because of their wider range of food.[144] In comparison with carnivorous fish, herbivorous and omnivorous fish are easier to mistake MPs drifting in water column for food.[145] For other large animals or mammals in the ocean, such as baleen whales, which filtered food out of large amounts of water, and tend to ingest MPs. Filter-feeding marine macro-fauna consumed a large amount of MPs mainly because of their filter feeding behavior. Most of the filter feeding animals contact with MPs by means of active or passive ingestion due to its in-distinguishability of feeding mechanisms.[146,147] In addition, the marine mammals without filter feeding systems, they still consume MPs.[148] When high concentrations of MPs in their habitats and feeding grounds, their intake of MPs is almost inevitable.[149]

3.3. Trophic transfer

The trophic transfer evidence of MPs is found by quantitative analysis of aquatic organisms collected in the field, their predators and animals raised in laboratory environmental studies.[16] It is known that there are nearly 700 species of aquatic organisms affected by MPs, and MPs can be observed in different nutrition levels.[150] The accumulation of MPs in low trophic organisms will have a linkage effect on food web.[151] MPs will migrate through the food web along with the predation of aquatic organisms. Lusher *et al.* found that MPs in high nutrient bio-excrement and tissues of different coastal habitats, which can be inferred that MPs could be accompanied by nutrient transfer when they are ingested directly.[152] The results showed that mussels *Mytilus edulus* exposed to PS MPs were fed to crab *Carcinus maenas*, MPs could be detected in *Carcinus maenas*.[153] Similarly, studies have fed several different zooplankton with PS MPs, and let mysid shrimps ingest these zooplankton, and finally they were transferred to shrimp.[154] In

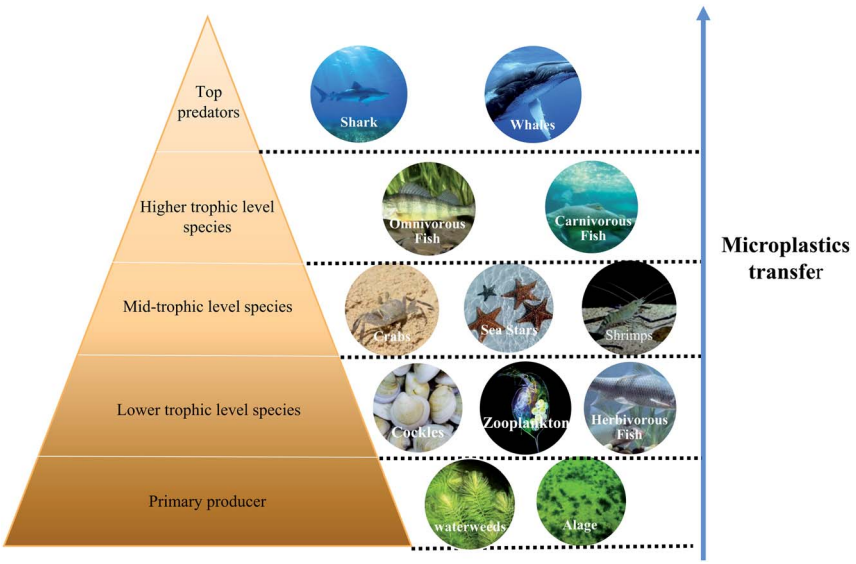

Fig. 3 Potential pathways of MPs for nutritional level migration in water environment.

addition to crustaceans and plankton, trophic transfer of MPs can also be found in vertebrates. MPs within the size range of many plankton are usually ingested by aquatic invertebrates, which are prone to be transferred to vertebrates at the higher end of the food chain.[155] Setala *et al.* found that the nutrient migration took place after three hours of contacting between macroplankton and medium-sized plankton-ingesting polystyrene MPs.[154] Potential pathways of MPs for nutritional level migration in water environment are shown in Fig. 3. Algae, which are located at the bottom of the food chain, are often transferred to higher trophic level organisms (such as plankton) after being ingested, which will have a certain impact on the whole ecosystem. However, some researchers believe that MPs can be rapidly purified in organisms, the possibility of having a great impact on high nutrient level organisms is very small.[16]

The residence time and the accumulation of MPs in biota is an important factor affecting trophic transfer. The longer the residence time, the easier the MPs transfer. For aquatic organisms, the concentration of MPs in the ingested environment may not be high.[156] But due to their retention and accumulation, the concentration of MPs in the body will be higher than that in environment.[156] The size and shape of MPs are also important factors.[40] In addition, individual differences of aquatic organism may affect residence time. The longer the residence time in biota, the easier the transferring of MPs along the trophic levels.[40] Moreover, the residence time of MPs varied in different organisms and different organs of the same organism (digestive tract, hepatopancreas, ovaries, gills), but generally shorter than those in blood.[153] Farrell and Nelson found that 24 hours after ingestion, the most abundant MPs were detected *in vivo*.[153] Different ways of ingesting MPs also lead to different residence time in organisms. For example, when crabs were exposed to polystyrene MPs, the residence time of MPs in gill obtained by air circulation was longer than that by direct ingestion *in vivo*.[157]

The research on the trophic transfer of MPs should not only focus on the MPs alone, but also on the carried pollutants. However, there are few studies on this topic can be found, and the effect of adsorption - desorption kinetics between MPs and pollutants in organisms (especially on advanced predators) is still unknown.[150] Due to the lack of data on the transfer of pollutants carried by MPs between organisms of high nutrient level and those of low nutrient level, the ecological risk assessment of MPs still need to be further studied.[150]

4. Conclusions and recommendations for future work

4.1. Conclusions

In freshwater environment, MPs mainly come from terrestrial and atmosphere environment, through sewage discharge, rainwater scouring and atmospheric sedimentation. For the marine environment, land dumping and freshwater systems contribute most of the MPs. These MPs are distributed in the surface water, water column, sediment and aquatic organisms in the aquatic systems. The most of the MPs in freshwater will flow into the ocean. Due to the degradation, the vast majority of MPs are cracked to the extent that we cannot detect the size or end up in the sediment. The migration of MPs can be divided into horizontal and vertical directions, which is closely related to the flow velocity, water depth, water flow variation, underwater topography, wind speed and MPs particles density.

The quantitative and qualitative analysis of MPs usually started with visual inspection with help of stereoscope or microscope, followed by spectroscopic methods, including FTIR, Raman spectroscopy, or thermos-analysis methods. Their advantages and disadvantages are summarized.

MPs as carriers of pollutants in water environment have an impact on biological communities. The factors affecting the ability of MPs to adsorb pollutants include hydrophobicity of adsorbed chemicals (K_{ow}), characteristics of MPs, weathering/aging of plastics, pH value and ionic strengthen of water. The coexistence of MPs with pollutants can promote the accumulation of these pollutants in aquatic organisms, which does not necessarily mean that the toxicity of these pollutant will be increased. Moreover, the hydrophobic surface of MPs can be easily to be colonized by bacteria or algae to form biofilm, which helps the migration of these organisms.

The trophic transfer of MPs along the food chain is mainly related to their residence time, accumulation, size and shape. The longer the residence time in biota, the easier the transferring of MPs along the trophic levels, and this will have a certain impact on the entire ecosystem. Overall, this review may help to enhance the understanding of the distribution, fate, and ecological impacts of MPs in aquatic system.

4.2. Recommendations of future work

In order to facilitate the comparison of MPs, the units to quantify MPs should be consistent or at least easy to convert. Meanwhile, the detection and analysis methods of MPs should be standardized, which is necessary for researchers to make valid comparison. To track and characterize the smaller size MPs, the detection and analysis methods need to be developed. For the ecotoxicological evaluation, large scale experiments need to be conducted to assess the effects of MPs combined with the pollutants they carry on aquatic biota, from molecular level to ecosystem level. Moreover, the negative effects of MPs with the carried pollutants on human health through food web are also encouraged to be explored.

Author contributions

All authors have made substantial contributions regarding the design and implement of the study. Yide He, Yunhai Zhang and Yongjun Zhang provided the funding. Yujie Cai, Rongwen Zhu, Ning Xu and Pow-Seng Yap provided the key intellectual input to the study and Sen Du wrote the manuscript. Yide He revised the manuscript. All authors approve the final manuscript.

Conflicts of interest

There are no conflicts to declare.

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