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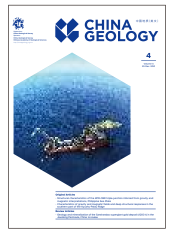

Microplastic pollution in Yellow River, China: Current status and research progress of biotoxicological effects

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A B S T R A C T

This study aims to comprehensively assess the environmental risks of microplastics in the Yellow River, achieving the following results through comprehensive research. The average microplastic abundances in the river waters and sediments are 5358–654000 n/m^3 and 43.57–615 items/kg, respectively, and there are fewer microplastics in water samples than in sediments. Microplastics in the study area can be divided into five types according to their occurrence morphologies, namely fragments, foams, films, fibers, and particles. The most widely distributed pollution types in sediments include debris, fibers, and particles. In contrast, fibers are the dominant type in water samples, accounting for 68.18%–98.93%. The chemical components of the microplastics include polyethylene, polypropylene, polystyrene, polyethylene terephthalate, and polyvinyl chloride. The microplastics are in four colors, with white accounting for a higher proportion. The grain size of the microplastics in tributaries or lakes of the Yellow River is less than 2 mm, which makes them liable to enter organisms for enrichment. Furthermore, the sources of the microplastics are closely related to agricultural and industrial production and biological activities in habitats and exhibit seasonal and hydrological characteristics. The microplastics in the study area show the adsorption of metals and nonmetals to different degrees, which increases the pollution risks of heavy metals combined with microplastics. In addition, microplastics can accumulate in organisms in the Yellow River and cause physical, biochemical, and other damage to aquatic organisms, thus further posing carcinogenic risks to human beings. Therefore, it is necessary to study, monitor, and control the pollution and effects of microplastics in the Yellow River, in order to provide theoretical references for the control of pollution and ecological risk of microplastics in the river.

1. Introduction

As early as the 1970s, it was reported that plastic particles were detected in ocean surface water (Carpenter EJ and Smith KL, 1972). Plastic products are widely used in modern society. The annual output of plastic products in the world has exceeded 3×10^8 t and is increasing at a rate of 0.2× 10^8 t/a (Ding JN et al., 2017). As a kind of high molecular polymer, plastic has excellent physical and chemical properties such as durability, water resistance, and strong corrosion resistance. It is widely used in all walks of life, but also causes environmental pollution. In recent years, microplastics have attracted great attention all over the world as a new type of pollutants. In 2004, British scholar Thompson first defined small-sized plastic particles as microplastics (Thompson RC et al., 2004), and academic circles generally took the particle size of less than 5 mm as the threshold of microplastics. Preliminary studies have shown that microplastics can migrate over long distances under the action of external forces, such

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as wind, rivers, and ocean currents. As a result, they are ubiquitous in ecosystems around the world. Microplastics have been found in the Mariana Trench, the deepest trench in the world (Johanna NJW et al., 2020), in the Himalayas (the roof of the world), and in many remote areas including the Antarctic and the Arctic (Syahir H et al., 2020, Kane IA et al., 2020; Kumar A et al.,2021).

Besides the marine environment, river systems also have a higher concentration of microplastics (He BB et al., 2021; Harpah N et al., 2021). Numerous pollution sources of microplastics have influenced the river environment, which may include tail water discharged from sewage treatment plants, the weathering and degradation of plastic wastes in water environment, and land-based input caused by soil erosion or surface runoff. The initial sources may include personal care products, synthetic textiles, industrial raw materials, and the improper disposal of plastic waste in towns, agriculture, tourism, and industrial areas. Microplastics will cause physical damage and biochemical stress to aquatic organisms in river systems and may form compound pollution coupled with other pollutants, resulting in serious ecological risks (Wright SL et al., 2013). Microplastics may even be transmitted through the food chain (Setälä O et al., 2014), thus threatening human health. Therefore, there is an urgent need for studying the pollution of microplastics in the river environment.

As the largest plastic producer and consumer in the world, China's plastic output accounted for 29.4% of the global total plastic output in 2017 alone (Plastics Europe, 2018). In 2014, microplastic pollution was reported for the first time in the eastern coastal areas of China (Zhao SY et al., 2014), and many researchers began to study the microplastic pollution in sediments in domestic rivers and lakes (Yan MT et al., 2019; Zhao SY et al., 2019).

As the mother river of China, the Yellow River have been previously studied in terms of the distribution status of the river water and microplastics in sediments in some major streams, tributaries, estuaries, lakes, and coastal farmland (Qin YM, 2020; Ding L et al., 2019; Hana M et al., 2020; Niu XR, 2020; Gong XL et al., 2020). Meanwhile, the toxicological effects of PVC microplastics on juvenile Cyprinus carpio have been investigated (Wang LL, 2019), and the health risk assessment of microplastics in the Yellow River Delta Wetland has been conducted (Zhao S, 2020). This paper summarizes the current status, sources, and ecotoxicological effects of microplastics in the Yellow River based on literature investigation, which can provide theoretical references for the study of pollution and ecological risks of microplastics in the river water environment in North China (Chen J, 2021).

2. Overview of the Yellow River

The Yellow River is the sixth longest river in the world and the second longest river in China, with a total length of 5464 km and a drainage area of about 752443 km^2. This river originates from Zhaqu of the Chahasila Mountain in the Bayankala Mountains of the Qinghai-Tibet Plateau, Kariqu at the northern foot of Qinghai Province, and Yuegu Zonglieq u in western Xingsuhai. It flows through Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong provinces (autonomous regions) from west to east and finally flows into the Bohai Sea, forming the "Π" shape (Fig. 1). The watershed of the Yellow River is in the range of 96° E–119° E and 32° N–42° N, with a length of approximately 1900 km from east to west, a width of approximately 1100 km from north to south, and an area of 7.95×10^5 km^2. It is high in the west and low in the east generally. According to the geographical, geological, and hydrological conditions of the formation and development of the river basin, the mainstream of the Yellow River can be divided into upper, middle, and lower reaches. The portion from Heyuan Town to Hekou Town, Toketo County, Inner Mongolia is the upper reaches, which has a length of 3471.6 km and a watershed area of 4.28×10^5 km^2, accounting for 53.8% of the total river watershed area. The portion from Hekou Town to Zhengzhou City, Henan Province is the middle reaches, which has a length of 1206.4 km and a watershed area of 3.44×10^5 km^2, accounting for 43.3% of the total watershed area. The remaining portion from Taohuayu, Henan Province to the estuary is the lower reaches, which has a flow area is 2.30×10^4 km^2, accounting for only 3% of the total area of the whole basin. The Yellow River flows through many cities. The sewage from these cities and the agricultural water in surrounding farmland may flow into the Yellow River. Moreover, environmental plastic waste may enter the sewage channels or agricultural water systems along with the runoff. All these cause pollution for the Yellow River. In addition, the woven packing bags of agricultural fertilizers and the random disposal of mulching films have also become potential sources of microplastic pollution.

3. Current status of microplastics

3.1. Abundance distribution of microplastics

Table 1, Fig. 1 shows average microplastic abundance in the upper, middle, and lower reaches of the Yellow River. According to this table, the average microplastic abundance in the surface water in the upper, middle, and lower reaches is 5358 n/m^3, approximately 8000 n/m^3, and 595270 n/m^3, respectively, and that at the estuary is 654000 n/m^3. Meanwhile, the average microplastic abundance in sediments in the upper, middle, and lower reaches is 43.57 items/kg, 54.29 items /kg, and 160 items/kg, respectively, and that at the estuary is 615 items/kg. Therefore, the average microplastic abundance in the Yellow River gradually increases from the upper reaches to the estuary. On the one hand, the plastics in the upper and middle reaches may migrate downstream along with the river water, and more plastics are enriched downstream. On the other hand, the cities in the lower reaches are located in coastal areas and feature relatively more developed economies and intensive human activities, which cause more serious microplastic pollution.

Table 1. Sampling sites and microplastic abundance in sediments of investigated lakes or rivers.

Reaches	Water sample No.	Average microplastic abundance in surface water/(n/m^3)	Reference	Sediment sample No.	Average microplastic abundance in sediment/items/kg	Average microplastic abundance in sediments/(n/m^3)	Reference
Upper reaches	H11-H18	5358	Qin YM, 2020	D12-D18	43.57	87140	Gong XL et al., 2020
Middle reaches	DH33	About 8000	Ding L et al., 2019	D5-D11	54.29	108580	
Downstream	H1-H9	595270	Hana M et al., 2020; Niu XR, 2020	D2-D4	160	320000	
Estuary	H10	654000	Hana M et al., 2020; Niu XR, 2020	D1	615	1230000	

Note: Average density of dry sediments is 1600 kg/m^3 (Fettweis M et al., 2007). When sampling results were presented as wet/dry in literature, a wet/dry ratio of 1.25 was applied for conversion (Van CL et al., 2015); H11-H18 water samples were taken from the surface water body of the lake, and other sample points from rivers.

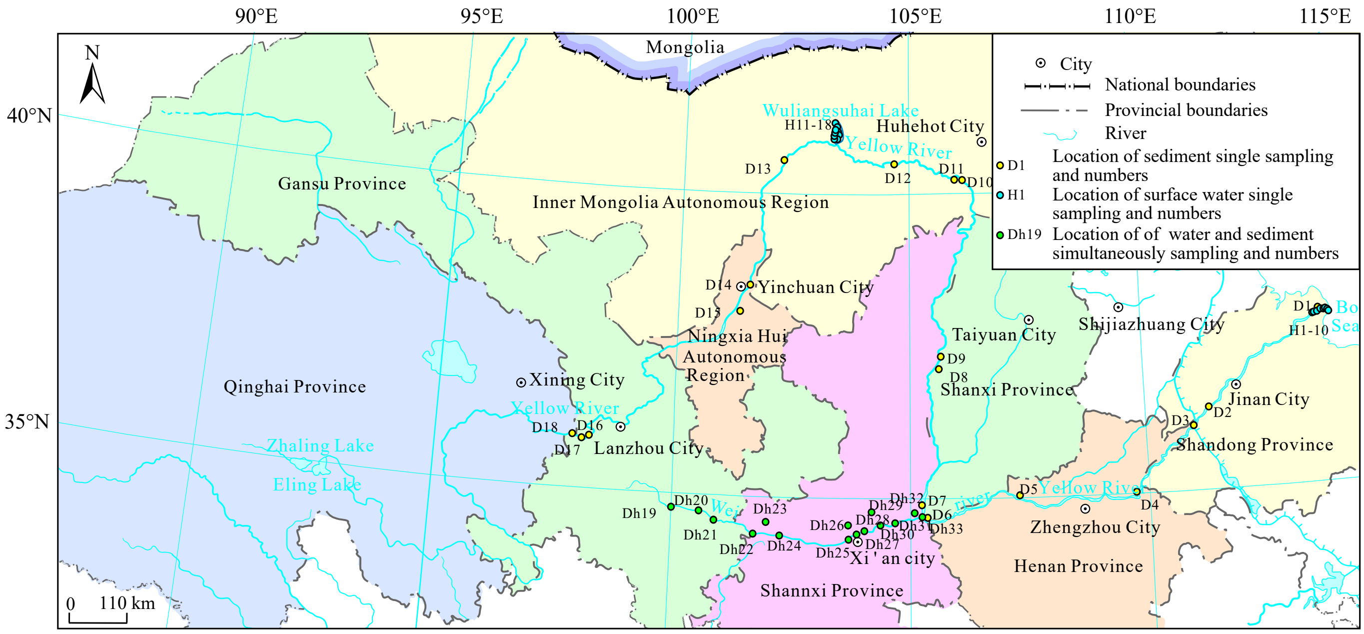

Fig. 1. Map showing the positions of microplastics in sediments and river water previously collected in the Yellow River.

3.2. Types of microplastics

The shape of microplastics affects their migration (such as floating and settling) in an aquatic environment and can be used to determine pollution sources. Therefore, it is of great significance to study the shape of microplastics. The microplastics in the mainstream of the Yellow River (from Gansu to the estuary) can be divided into four types according to their occurrence morphologies, namely debris, foamed plastics, films, and fibers (Gong XL, 2020). Among them, the debris has the highest debris content of 41.97%, which is followed by the foamed plastics, which has content of approximately 34.08%. Meanwhile, the films and fibers jointly account for 23.95%. Particles were detected in the sediments of the Weihe River, a tributary of the Yellow River. They are dominated by fiber, which accounts for 42.25%–53.20%, followed by films and fragments, which account for 23.9%–31.8% and 10.2%–20.3%, respectively (Ding L et al., 2019). Fibrous microplastics are dominant in water samples of the Yellow River, with the content ranging from 68.18% to 78.64% (Qin YM, 2020), and fiber is dominant in water samples from the lower reaches of the Yellow River. The collected microplastics include polyethylene (PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), and Polyvinyl chloride (PVC), which are dominated by PP. Microplastics separated from water and sediment samples of the Yellow River can be divided into four types according to their colors, namely transparent, white, colored, and black microplastics. Among these types, transparent and white microplastics account for a higher proportion in the rivers, while colored microplastics have high concentration in the Wuliangsuhai Lake. This may be closely related to domestic garbage. In terms of grain size, except for the mainstream of the Yellow River, the grain size of tributaries or lakes is less than 2 mm (Table 2).

4. Discussion and suggestions

4.1. Causes for microplastic pollution

Microplastics are widely distributed in the water environment of the Yellow River, with waters such as rivers,

Table 2. Types and characteristics of microplastics in the sediments or waters in the Yellow River.

Reaches	Sample type	Microplastic types by morphology					Microplastic types by color				Grain size	Component	Reference
		Fiber	Fragment	Foams	Films	Pellets	Trans-parent	White	Colored	Black			
Mainstream of river	Sediments	A few	43.35%	34.08%	A few		43.28%	34.55%			1–4 mm	PE, PS, and PP	Gong XL et al., 2020
Yellow River Delta wetland	Sediments	8.91%–31.27%	17.93%–43.80%		A few	24.28%–72.42%	/	/	/	/		Mainly PS	Zhao S, 2020
Weihe River	Sediments	42.25%–53.20%	10.2%–20.3%	0.7% –3.5%	23.9%–31.8%	5.6%–16.1%	/	/	/	/	<0.5 mm: 40.8%–68.8%; 0.5–1 mm: 8.35%–24.2%	PE, PVC, and PS	Ding L et al., 2019
Weihe River	River waters	38.25%–61.95%	10.6%–21.7%	0.25% – 3.5%	17.4%–38.2%	0.4%–7.8%	/	/	/	/	<0.5 mm: 40.8%–68.8%; 0.5–1 mm: 15.1%–27.1%	PE, PVC, and PS	Ding L et al., 2019
Wuliangsuhai Lake	Lake waters	68.18%–78.64 %	5.4%		8%–10%	2.6%–11.4 %			71.5%–94.9%		<2 mm: 74.74% on average	PE, PS and, PET	Qin YM, 2020
Estuary	River waters	86.45%–98.93%	0.04%–7.60%			0.62%–10.63%	Trans-parent and white mostly	A few are black or colored	<0.2 mm: 92.95%			PE, PS, and PP	Niu XR, 2020

Note: "/" indicates no data description.

lakes, and estuary being polluted by microplastics to different degrees. Meanwhile, the distribution of microplastics differs in different water bodies, the reasons for which include population density, human activities, seasons, hydrological characteristics, and the nature. In addition, the sampling and analytical methods of microplastics also affect the distribution of microplastics (Fig. 2).

(i) Population density and human activities are closely related to the distribution of microplastics in the Yellow River. Taking the distribution of microplastics in the river water and sediments of the Weihe River as an example (Ding L et al., 2019), the microplastic abundance in the surface water at sampling sites Dh19–Dh33 (Fig. 1) varies in the range of 3.67–10.7 items/L (360–1320 items/kg). Meanwhile, sampling sites with microplastic abundance of higher than 6.5 items/L are almost located in densely populated areas and agricultural planting areas. Agricultural production and anthropogenic activities may lead to the presence of plastic waste and other pollutants in the Weihe River (Wang WZ et al., 2018). Among them, sample sites DH20, Dh22, Dh25, and Dh2 are located in the densely populated Tianshui, Baoji, Xianyang and Xi'an cities, which are the four big cities where the Weihe River flows through.

Fiber microplastics may be attributed to the decomposition of agricultural equipment and sewage containing clothing fibers to a great extent (Claessens M et al., 2011). Microplastics have been detected in the farmland soil along the Fenhe and Weihe rivers-tributaries of the Yellow River, and the detected microplastics include fibers, films, fragments, and foams, among which the fibers have the highest concentration (Zhu YE et al., 2021, Ding L et al., 2019) Thin films are also widely distributed in the surface water and sediments, which account for 17.4%–38.2% and 23.9%–31.8% of microplastics in the surface water and sediments, respectively. Domestic sewage containing plastics is an important source of microplastics in the Yellow River (Wang WF et al., 2018). In addition, with the development of farming and agricultural activities, the insulation film-based greenhouse cultivation technology in modern facility agriculture has increased the films in water and sediments, which can be considered another source of film microplastics in the Yellow River. Taking the Weihe River as an example, the microplastic abundances in sediments and surface water are 23.9%–31.8% and 17.4%–38.2%. Fragments have been found in almost all river reaches and lakes. 43.35% of the microplastics fragments may come from the decomposition of much plastic waste, such as agricultural implements, plastic packaging materials, plastic woven bags, and plastic bags (Antunes JC et al., 2013). Although they are relatively small in quantity, particulate and foam microplastics are also found in sediment samples and water samples from the Weihe River. Many personal care products and artificial plastic products can cause particulate pollution. Zhao S (2020) studied the uninhabited wetland protected areas, tourist areas with numerous tourism activities, and port areas with dense freight and shipping in the Yellow River Delta and discovered that the particle shape of microplastics was on the high side. PS is the main material in microplastics, which is one of the commonly used materials and mainly exists in the form of particles in coastal environments (Li XW et al., 2018). Foams may come from packaging materials and plastic containers (Nur HMN and Jeffrey PO, 2014). Therefore, industrial manufacturing and domestic sewage may be potential sources of microplastics (Di MX and Wang J, 2018); thus the microplastic types are related to human activities (Fig. 2).

(ii) The distribution of microplastics in the Yellow River differs in different seasons. For example, the microplastic abundance at the estuary is 654 items/L and 930.2 items/L, respectively in wet and dry seasons, with the microplastic abundance in the dry period greater than that in the wet period (Niu XR, 2020). The microplastic abundance at the Yangtze River estuary (Zhao SY et al., 2019) and in the Nakdong River is noticeably higher in rainy seasons than in other seasons (Eo S et al., 2019). The differences in the microplastic content in surface water and sediments of the Antuã River between March and October (Rodrigues MO et al., 2018) also indicate that season is an important influencing factor of the distribution of microplastics. The authors think that the comparison results of the microplastic abundance in the rivers in wet seasons with that in dry seasons need to be further verified. Hydrological characteristics also affect the distribution of microplastics. The microplastic content in relatively closed and stable lakes and wetlands in the Yellow River Basin is generally high. For example, the overall microplastic abundance in the Yellow River Delta wetland is 80–4640 items/kg, with an average abundance of 1142.53 items/kg (Zhao S, 2020). In contrast, the average microplastic abundance in the sediments of the Yellow River estuary is 615 items/kg (Gong XL et al., 2020), and it is also high in the Qinghai Lake (Liu RP et al., 2021) and Taihu Lake (Su L et al., 2016) in China, and the Winnipeg Lake (Sruthy S and Ramasamy EV, 2017) abroad. However, for rivers with weak hydrodynamic conditions, the microplastics will be gradually deposited. The research on the microplastics in the Yellow River shows that the microplastic content in water samples is lower than that in sediment samples, which is mainly due to the accumulation of microplastics and the influence of high sand content on the distribution of microplastics. In addition, the distribution of microplastics is related to the nature of microplastics. For example, some microplastics surfaces can quickly form biofilms, which gradually accumulate and enter the sediments (Chen XC, 2019). Compared with low-density microplastics, high-density microplastics are more liable to sink from water into sediments (Di MX and Wang J, 2018). Similarly, more low-density polyethylene films are visible at the Yellow River estuary and coastal zones (Zhang CJ, 2021).

4.2. Biotoxicological effects

(i) Owing to water erosion and direct sunlight, microplastics are primarily affected by mechanical wear, high temperature oxidation, and ultraviolet radiation. These lead to the changes in the molecular structure of microplastic polymers, including molecular bond breaking and disproportionation. As a result, smaller microplastics and even nano-scale plastics will be formed. There are cracks, holes, curls, and tears on the surface of weathered microplastics. These microscopic characteristics of microplastics provide a wide range of attachment sites for other elements, which may lead to the superimposition effect of microplastic pollution and metal pollution (Liu J et al., 2020). Metal and nonmetal elements have been detected on the surface of microplastics in the surface water and sediments in the Yellow River, which increase the hazards risks of the microplastics.

As mentioned above, main components of the microplastics in the Yellow River include PE, PVC, PS, PP, and PET, which are highly harmful to aquatic organisms in the Yellow River. Zhao S (2020) found that PS with different particle sizes can adhere to the chorion of zebrafish, and nano-scale PS can accumulate in the gill of larval fish, enter blood circulation, and gradually accumulate in the brain and liver of larval fish. PS with different particle sizes have toxic effects on zebrafish and cause inflammatory effects for target organs (liver), which will change the metabolic pathways related to the antioxidant defense system of zebrafish used to resist the oxidative stress induced by microplastic exposure. Moreover, nano-scale PS has stronger toxic effects than micro-scale PS (Zhao S, 2020). However, different concentrations of polyvinyl chloride and PVC can inhibit the normal growth of juvenile yellow river carps, disturb the expression of genes related to gonad development and the normal formation of tissue structure, and induce oxidative damage and changes in immune system function (Wang LL, 2019). Other types of microplastics have not been discovered in the study area, but relevant studies show that PE, PET, and PP will also affect the feeding activities and energy reserves of aquatic organisms (Silva CJM et al., 2019; Weber A et al., 2018; Ding GH, 2020).

(ii) Microplastics pose some health risks to human body. According to Zhao S (2020), microplastics in the Yellow River Delta wetland have potential carcinogenic risks to human health under the exposure route of skin contact. Therefore, microplastics in the Yellow River area must be managed and controlled by relevant departments.

4.3. Suggestions

The control over microplastic pollution is crucial, which however is restricted by relevant techniques, laws, people's ideologies. Therefore, the control of the microplastic pollution in the Yellow River is an urgent scientific proposition to be solved. Given this, the authors put forward some suggestions to be referred to by relevant departments, scientists, and technological professionals.

(i) Improve investigation and monitoring: the current investigation of microplastics in the Yellow River Basin and even in the whole country is arranged only in a point or linear form instead of spatial network monitoring. This presents a certain challenge for accurate early warning and later forecasting. In the future, large quantities of human resources are required for microplastic monitoring. It is suggested to give full play to the application of remote sensing technology

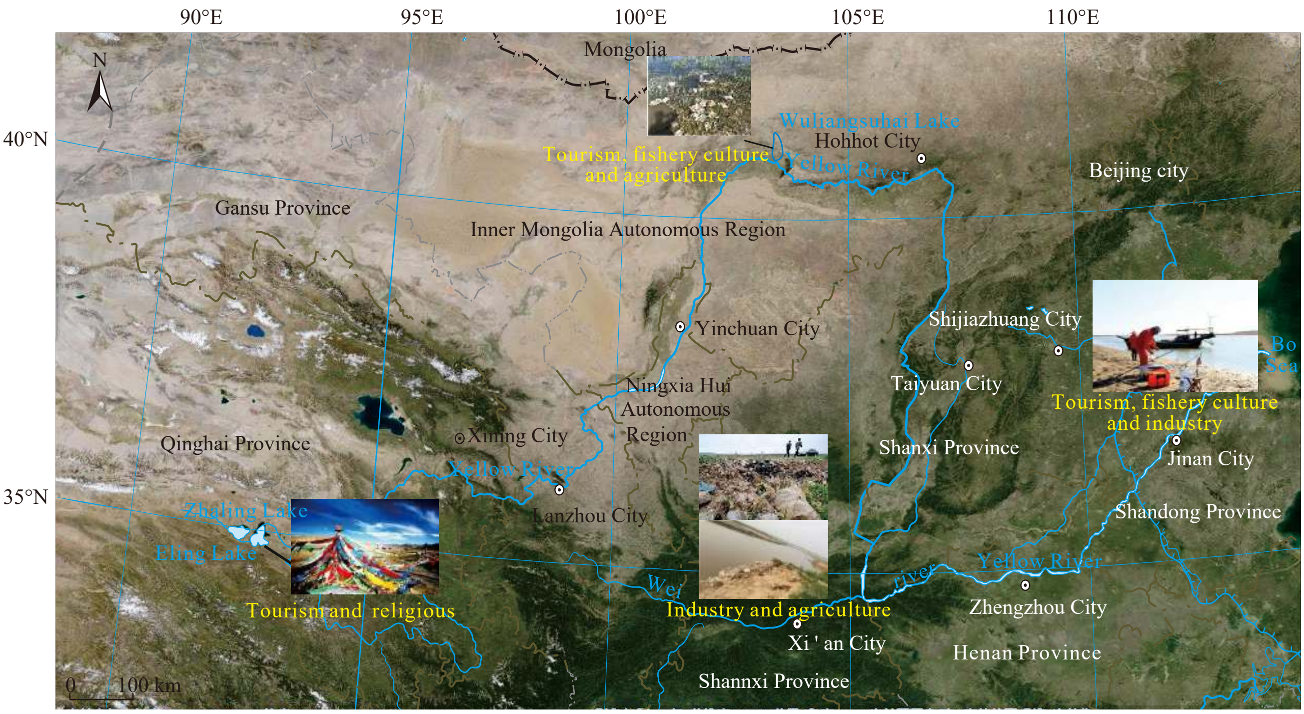

Fig. 2. Sources of microplastics in typical rivers in the Yellow River basin

in microplastic investigation and monitoring and to carry out practice of multiple sciences in this respect (Elizabeth CA et al., 2019).

(ii) Strengthen the formulation of control and access regulations. Firstly, control microplastic sources, formulate plastic management measures, and rationally handle plastic waste. Second, reform the microplastic treatment equipment in daily production, reduce the production of primary microplastics, and improve the recycling rate of secondary plastic products. Thirdly, manage and restrict the use of plastic products by legal means to reduce the emission of microplastics into the environment. A series of national-level systems and programs have been issued since 2007 (Li TC et al., 2021), which however are difficult to implement and suffer slow implementation progress. In addition, laws and regulations on plastic waste management are yet to be improved, and it is necessary to implement the target-oriented responsibility system and punishment system of plastic waste, such as rural plastic film recycling and the garbage including express bags and take-away bags.

(iii) Develop degradable plastics. It is necessary to develop environmentally friendly degradable plastics. In the case that microplastics exist longer in the water environment than on land, they are more difficult to degrade, which can be well avoided by using degradable plastics. Scientists have developed degradable plastics. For example, rice hull ash (RHA)-an industrial waste material-has been used as a reinforcing filler to melt together with polybutylene succinate (PBS) to prepare biodegradable composites of polyhydroxyalkanoate (RHAs)/PBSs (Cao XW et al., 2020). Meanwhile, it is necessary to formulate the standards of degradable plastics (Wang XJ et al., 2021) to ensure the effective degradation of microplastics.

(iv) Strengthen environmental awareness education. At present, the attention paid to the hazards of microplastics is still insufficient, and the public in the world still only possess weak awareness on garbage classification and poor knowledge about the science popularization of environmental protection. It is necessary to give full play to the Internet to popularize the knowledge about microplastic-induced hazards and environmental safety risks and garbage classification. The purpose is to achieve unified public knowledge and practice and to effectively classify and manage garbage.

5. Conclusions and prospect

(i) Microplastics have been found in all the water and sediment samples from the Yellow River. Moreover, the abundance of microplastics in these sediments is relatively high. However, this study shows that there are fewer microplastics in the water samples than in the sediment samples. The study results demonstrate that the low-velocity flow and high sand content increase the accumulation and distribution of microplastics. In addition, the microplastic sources in the Yellow River are closely related to agricultural and industrial production and biological activities in habitats.

(ii) At present, the investigation of the microplastic pollution in the Yellow River Basin is only in a preliminary and disorganized pattern, while lacking a systematical monitoring network. This poses a certain challenge for accurate early warning and later forecasting.

(iii) Complex factors are involved in microplastic biotoxicity and in the exposure of freshwater organisms to microplastics in the Yellow River, which should be studied by combining specific environmental conditions (e.g., hydraulic condition) in the future to better assess the microplastic biotoxicity to freshwater organisms and human beings.

CRediT authorship contribution statement

Rui-ping Liu conceived of the presented idea. Rui-ping Liu and Zhi-zhong Li developed the theory and performed the computations. Rui-ping Liu investigated microplastic pollution and supervised the findings of this work. All the authors discussed the results and contributed to the final manuscript.

Declaration of competing interest

The authors declare no conflicts of interest.

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References

Antunes JC, Frias JGL, Micaelo AC, Sobral P. 2013. Resin pellets from beaches of the portuguese coast and adsorbed persistent organic pollutants. Estuarine, Coastal and Shelf Science, 130, 62–69. doi: 10.1016/j.ecss.2013.06.016.

Carpenter EJ, Smith KL. 1972. Plastics on the Sargasso Sea surface. Science. 175(4027), 1240–1241. doi: 10.1126/science.175.4027.1240.

Cao XW, Peng JJ, He GJ. 2020. Properties of RHA/PBS Biodegradable Plastics. Modern Plastics Processing and Applications, 32(3), 1–4.

Chen XC, Xiong X, Jiang XM, Shi HH, Wu CX. 2019. Sinking of floating plastic debris caused by biofilm development in a freshwater lake. Chemosphere, 222, 856–864. doi: 10.1016/j.chemosphere.2019.02.015.

Chen J, Gao YY, Qian H, Jia H, Zhang QY. 2021. Insights into water sustainability from a grey water footprint perspective in an irrigated region of the Yellow River Basin. Journal of Cleaner Production, 316, 128329. doi: 10.1016/j.jclepro.2021.128329.

Claessens M, Meester SD, Landuyt LV, Clerck KD, Janssen CR. 2011. Occurrence and distribution of microplastics in marine sediments along the Belgian coast. Marine Pollution Bulletin, 62(10), 2199–2204. doi: 10.1016/j.marpolbul.2011.06.030.

Ding GH. 2020. Distribution of Microplastics and Their Uptake and Elimination in Zooplankton in the Bo Sea and the Yellow Sea. Dalian, Dalian Maritime University, Master's Thesis, 1–80 (in Chinese with English abstract).

Ding JN, Zhang SS, Zou H, Zhang Y, Zhu R. 2017. Occurrence, source and ecotoxicological effect of microplastics in freshwater environment. Ecology and Environmental Sciences, 26(9), 1619–1626 (in Chinese with English abstract). doi: 10.16258/j.cnki.1674-5906.2017.09.023.

Di MX, Wang J. 2018. Microplastics in surface waters and sediments of the Three Gorges Reservoir, China. Science of the total environment. 616(1), 1620–1627.

Ding L, Mao RF, Guo XT, Yang XM, Zhang Q, Yang C. 2019, Microplastics in surface waters and sediments of the Wei River, in the northwest of China. Science of the Total Environment, 667, 427–434. doi: 10.1016/j.scitotenv.2019.02.332.

Elizabeth CA, Francesco MFP, Mathias B, Michael M, Jonas F, Sandro C, Mauro S, Christian L, Florian Siegert. 2019. Coastal accumulation of microplastic particles emitted from the Po River, Northern Italy: Comparing remote sensing and hydrodynamic modelling with in situ sample collections. Marine pollution bulletin, 138(1), 561–574. doi: 10.1016/j.marpolbul.2018.11.045.

Eo S, Hong SH, Song YK, Han GM, Shim WJ. 2019. Spatio-temporal distribution and annual load of microplastics in the Nakdong river, South Korea. Water Research, 160, 228–237. doi: 10.1016/j.watres.2019.05.053.

Fettweis M, Du FI, Zeelmaekers E, Baeteman C, Francken F, Houziaux JS, Mathys M, Nechad, B, Pison V, Vandenberghe N. 2007. Mud Origin, Characterisation and Human Activities (MOCHA). Final Scientific Report, 1–59.

Gong XL, Zhang DY, An XL. 2020. Pollution and characterization of microplastics in the sediments of the Yellow River. Arid zone research, 37(3), 790–798. doi: 10.1002/wer.1275.

Hana M, Niu X, Tang M, Zhang BT, Wang GQ, Yue WF, Kong XL, Zhu JQ. 2020. Distribution of microplastics in surface water of the lower Yellow River near estuary. Science of the Total Environment 707, 135601. doi: 10.1016/j.scitotenv.2019.135601.

Harpah N, Ageng P, Addauwiyah R, Rizki A, Perdana Z, Suryati I, Leonardo R, Husin A, Faisal M. 2021. Microplastic pollution in Deli Rive Medan. Earth and Environmental Science, 802, 012019. doi: 10.1088/1755–1315/802/1/012019.

He BB, Mitchell S, Prasanna E, Godwin AA, Llew R, Ashantha G. 2021. Dispersal and transport of microplastics in river sediments. Environmental pollution, 279, 116884. doi: 10.1016/j.envpol.2021.116884.

Johanna NJW, Priscilla C, Thomas DL, William DKR, Alan JJ. 2020. New species of Eurythenes from hadal depths of the Mariana Trench, Pacific Ocean (Crustacea: Amphipoda). Zootaxa, 4748(1), 1175–5326. doi: 10.11646/zootaxa.4748.1.9.

Kane IA, Clare MA, Miramontes E, Wogelius R, Rothwell JJ, Garreau P, Pohl F. 2020. Seafloor microplastic hotspots controlled by deep-sea circulation. Science, 368(6495), 1140–1145. doi: 10.1126/science.aba5899.

Kumar A, Diptimayee B, Sharmila B, Praveen KM, Yadav A. 2021. Distribution and characteristics of microplastics and phthalate esters from a freshwater lake system in Lesser Himalayas. Chemosphere, 283, 131132. doi: 10.1016/j.chemosphere.2021.131132.

Li TC, Huang XL, Wu CX, Guo WS. 2021. Microplastic pollution in the Yangtze River Basin: Status quo and control measures. Journal of Yangtze River Scientific Research Institute, 38(6), 143–150. doi: 10.11988/ckyyb.20210057.

Li XW, Chen LB, Mei QQ, Dong B, Dai XH, Ding GJ, Zeng EY. 2018. Microplastics in sewage sludge from the wastewater treatment plants in China. Water Research, 142, 75–85. doi: 10.1016/j.watres.2018.05.034.

Liu J, Dai Y, Yao QW, Zhang J. 2020. Distribution status and characteristics of microplastics in water environment: A review. Guangdong chemical industry, 47(16), 93–94 (in Chinese with English abstract).

Liu RP, Ying D, Quan GC, Zhu H, Xu YN, Elwardany RM. 2021. Microplastic pollution in surface water and sediments of Qinghai-Tibet Plateau: Current status and causes. China Geology, 4, 178−184. doi: 10.31035/cg2021011.

Niu XR. 2020. Study on the Occurrence Characteristics of Microplastics in the Surface Water of the Yellow River Estuary. Jinan, Shandong Normal University, Master's Thesis, 1–83 (in Chinese with English abstract).

Nur HMN, Jeffrey PO. 2014. Microplastics in Singapore's coastal mangrove ecosystems. Marine Pollution Bulletin. 79(1–2), 278–283. doi: 10.1016/j.marpolbul.2013.11.025.

Plastics Europe. 2018. Plastics the facts 2017 an analysis of Europen plastics production, demand and waste data. 18 –19. https://www.plasticseurope.org/en/resources/market-data.

Qin YM. 2020. Pollution Characteristics and Risk Assessment of Microplastics in Lake Ulansuhai. Baotou, Inner Mongolia University of Science and Technology, Master's thesis, 1 –53 (in Chinese with English abstract).

Rodrigues MO, Abrantes N, Goncalves FJM, Nogueira H, Marques JC, Gonçalves AMM. 2018. Spatial and temporal distribution of microplastics in water and sediments of a freshwater system (Antuã River, Portugal). Science of the Total Environment, 633(1), 1549–1559. doi: 10.1016/j.scitotenv.2018.03.233.

Setälä O, Fleming-lehtinen V, Lehtiniemi M. 2014. Ingestion and transfer of microplastics in the planktonic food web. Environmental Pollution, 185(3), 77–83. doi: 10.1016/j.envpol.2013.10.013.

Syahir H, Anastasia I, Mohd YAS, Siti AA, Jerzy S, Nur AY. 2020. Biodeterioration of untreated polypropylene microplastic particles by Antarctic bacteria. Polymers, 12, 2616. doi: 10.3390/polym12112616.

Su L, Xue Y, Li L, Yang DQ, Kolandhasamy P, Li DJ, Shi HH. 2016. Microplastics in Taihu lake, China. Environmental Pollution, 216(16), 711–719. doi: 10.1016/j.envpol.2016.06.036.

Sruthy S, Ramasamy EV. 2017. Microplastic pollution in Vembanad Lake, Kerala, India: The first report of microplastics in lake and estuarine sediments in India. Environmental Pollution, 222(16), 315–322. doi: 10.1016/j.envpol.2016.12.038.

Silva CJM, Silva ALP, Gravato C. 2019. Ingestion of small sized and irregularly shaped polyethylene microplastics affect Chironomus riparius life-history traits. Science of the Total Environment, 672, 862–868. doi: 10.1016/j.scitotenv.2019.04.017,.

Thompson RC, Olsen Y, Mitchell RP, Davis A, Rowland SJ, John AW, Mcgonigle D, Russell AE. 2004. Lost at sea: Where is all the plastic? Science, 304(5672), 838–838.

Van CL, Claessens M, Vandegehuchte MB, Janssen CR, 2015. Microplastics are taken up by mussels (Mytilus edulis) and lugworms (Arenicola marina) living in natural habitats. Environment Pollution. 199, 10–17. doi: 10.1016/j.envpol.2015.01.008.

Wang LL. 2019. Study on Toxicological Effects of Pvc Microplastics on Juvenile Yellow River Carp. Xinxiang, Graduate School of Henan Normal University, Master's Thesis, 1 –67 (in Chinese with English abstract).

Wang WZ, Song JX, Zhang GT, Liu Q, Guo WQ, Tang B, Cheng, DD, Zhang Y. 2018. The influence of hyporheic upwelling fluxes on inorganic nitrogen concentrations in the pore water of the Weihe River. Ecological Engineering, 112, 105–115. doi: 10.1016/j.ecoleng.2017.12.012.

Wang WF, Yuan WK, Chen YL, Wang J. 2018. Microplastics in surface waters of Dongting Lake and Hong Lake, China. Science of the Total Environment, 633(1), 539–545. doi: 10.1016/j.scitotenv.2018.03.211.

Wang XJ, Sun DW, Feng JL, Zhou YH. 2021. Status and Prospect of Evaluation Standards on Degradable Plastics. China Plastics Industry, 49(6), 1–5 (in Chinese with English abstract).

Weber A, Scherer C, Brennholt N, Reifferscheid G, Wagner, M. 2018. PET microplastics do not negatively affect the survival, development, metabolism and feeding activity of the freshwater invertebrate Gammarus pulex. Environmental Pollution, 234, 181–189. doi: 10.1016/j.envpol.2017.11.014.

Wright SL, Thompson RC, Galloway TS. 2013. The physical impacts of microplastics on marine organisms: a review. Environmental Pollution, 178(13), 483–492. doi: 10.1016/j.envpol.2013.02.031.

Yan MT, Nie H, Xu KH, He YH, Hu YT, Huang YM, Wang J. 2019. Microplastic abundance, distribution and composition in the Pearl River along Guangzhou city and Pearl River estuary, China. Chemosphere, 217, 879–886. doi: 10.1016/j.chemosphere.2018.11.093.

Zhang CJ, Tu C, Zhou Q, Li LZ, Li Y, Fu CC, Pan XL, Luo YM. 2021. Weathering characteristics of microplastics of low density polyethylene film in the coastal environment of the Yellow River Estuary. Acta Pedologica Sinica, 58(2), 456–463. doi: 10.11766/trxb201912250697.

Zhao SY, Wang T, Zhu LX, Xu P, Wang XH, Gao L, Li DJ. 2019. Analysis of suspended microplastics in the Changjiang Estuary: implications for riverine plastic load to the ocean. Water Research, 161, 560–569. doi: 10.1016/j.watres.2019.06.019.

Zhao SY, Zhu LX, Wang T, Li DJ. 2014. Suspended microplastics in the surface water of the Yangtze Estuary System, China: first observations on occurrence, distribution. Marine Pollution Bulletin, 86(1–2), 562–568. doi: 10.1016/j.marpolbul.2014.06.032.

Zhao S. 2020. Microplastic survey and health risk assessment of wetlands in the Yellow River Delta. Tianjin, Tianjin University of Technology, Master thesis, 1–57 (in Chinese with English abstract).

Zhu YE, Wen HX, Li THX, Li H, Wu C, Zhang GX, Yan J. 2021. Distribution and sources of microplastics in farmland soil along the Fenhe River. Environmental Science, 42(8), 3894–3904. doi: 10.1016/j.scitotenv.2020.143860.