



Characterization of Microplastic Contamination and Risk Assessment in the Surface Waters of Rural Rivers in South China

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Received: 22 February 2024 / Accepted: 7 August 2024
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Abstract Microplastics (MPs) are ubiquitous in the environment and may threaten the ecosystem. Currently, research on MP pollution in China has focused on urban and coastal areas. To better understand the extent of MP pollution in the surface water of rural areas, we investigated the abundance, particle size, color, shape, and polymer chemical characteristics of MPs in the Longjiang River in China during the wet season (August) and dry season (December). The results showed that MPs were detected at all 12 sampling sites in August and December, with higher mean abundances observed in August (112.60 ± 5.63 items/m³) than in December (49.34 ± 2.47 items/m³). The predominant particle sizes of the MPs ranged from 100–500 µm, transparent was the most common appearance, and debris was the most common

shape. Chemical characterization revealed that polyethylene (PE) and polyvinyl chloride (PVC) were the major polymer types. Correlation analysis indicated that agricultural film usage was the primary source of MP pollution in the Longjiang River basin. Risk assessments were conducted based on the chemical characteristics and abundances of MPs, revealing a high risk level due to the presence of hazardous PVC. However, the overall potential ecological level of MP pollution in the Longjiang River basin was lower than that observed in urban areas due to the lower abundances and pollution loads. This study provides valuable baseline data to assess the environmental risks associated with MPs and serves as a basis to formulate effective environmental policies.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11270-024-07422-9>.

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Keywords Rural areas · Surface water · Microplastics · Risk assessment

1 Introduction

Microplastics (MPs) are generally considered plastic particles less than 5 mm in size (Barnes et al., 2009) and can be primarily classified as primary or secondary MPs (González-Pleiter et al., 2019). Industrial production and domestic activities generate substantial amounts of MPs, with secondary MPs being the predominant contributors to MP pollution in water bodies (Jiang, 2018). Researchers have discovered that MPs severely harm the ecological environment

(Wang et al., 2021a). Organic pollutants and heavy metals present in water are absorbed by MPs. Due to wear and photooxidation, MPs with smaller particle sizes exhibit enhanced adsorption capacity, resulting in negative surface charges (Wang et al., 2021b). These toxic MP composites are likely to be ingested by organisms and enter the food chain, posing crucial security risks to humans (González-Pleiter et al., 2019).

MPs have been found worldwide, with water environments particularly affected. MPs can be detected in oceans, rivers, reservoirs, and tap water (Razeghi et al., 2021). Most oceanic MPs originate from land, and their distribution patterns in the ocean have been extensively studied by researchers. However, there is a relative lack of research on the characteristics and distribution of MPs in freshwater bodies (Frias et al., 2016; Razeghi et al., 2021). Current studies on MP pollution in freshwater rivers in China have focused on the Pearl River (Lin et al., 2018; Yan et al., 2019), the Yangtze River estuary (Di & Wang, 2018; Wu et al., 2022), and economically highly developed areas along the southeastern coast (Li et al., 2021b; Xu et al., 2018). In contrast, there is limited research on MPs in freshwater environments in southern China (Zhou et al., 2020), especially in rural freshwater rivers. The study of MP pollution in freshwater rivers is meaningful (Gong et al., 2022), especially considering the abundance of rural freshwater rivers in South China. Therefore, it is crucial to investigate and prevent potential MP pollution in surface water environments in rural areas.

The Longjiang River, which is the largest tributary of the Liujiang River and belongs to the upper reaches of the Pearl River system, originates in Sandu County, Guizhou Province. It is an inland river that flows primarily through Hechi city in the Guangxi Zhuang Autonomous Region before meeting the Rongjiang River in Liuzhou city to form the Liujiang River. The wet season for the Longjiang River typically runs from April to September, and the Longjiang River has a catchment area of 16,878 km² with a total length of 367 km. The Longjiang River is abundant in hydropower resources, with several dams constructed along its course. This river is a vital source of drinking water for millions of residents in the downstream city of Liuzhou. Additionally, water pollution in the Longjiang River critically impacts the Pearl River basin. Agriculture is highly developed in

the river basin, with more than 7530 km² of farmland cultivated in 2019. The major crops grown in this area include vegetables (2160 km²) and sugarcane (1300 km²), according to government statistics. The total amount of agricultural film usage for the entire year surpassed 2×10^6 kg, and fertilizer usage exceeded 3.3×10^8 kg. The extensive use of agricultural films (Liu et al., 2017) and fertilizers (Yang et al., 2021) inevitably leads to contamination of both land and rivers. In response, the local government emphasized regulating agricultural film usage and fertilizer application in 2020, promoting recycling and reusing agricultural films, and reducing fertilizer usage to increase efficiency. Addressing MP pollution in the Longjiang River and other water bodies in China necessitates a long-term and sustained effort, as well as a comprehensive approach that considers the social and economic aspects of the issue. Protecting water resources in the Longjiang River is vital to ensure food production safety, public health, and socioeconomic development in the surrounding areas.

In the present study, we investigated the characteristics of MPs pollution in the surface water of the Longjiang River, a major tributary of the Liujiang River in China. Sampling was conducted at selected major tributaries within the Longjiang River before and after the confluence section, with variations in the abundance, size, color, shape, and polymer chemical distribution of MPs analyzed during August (wet season) and December (dry season). The MP pollution data were compared to those from more economically developed areas, such as the Pearl River downstream region. Potential sources of pollution were also identified by combining water quality indicators from the same period. Hazard scores for MP polymers by Lithner et al. (Lithner et al., 2011) were used to assess the MPs-induced risk index (H), and the pollution load index (PLI) and potential ecological risk index (RI) were assessed using established assessment models (Li et al., 2020; Xu et al., 2018). This study represents the first baseline investigation of MP pollution in the Longjiang River, and we aimed to provide data support for the management of MP pollution in the basin as well as references for research on MP pollution in rural areas.

2 Materials and Methods

2.1 Sampling

The study samples were collected during August (wet season) and December (dry season) in 2020. Microplastic samples were conducted using a shallow water type III plankton net with an aperture of 74 μm , following the methods of Manca et al. (Kovac Virsek et al., 2016), at 12 sections along the Longjiang River. The location information for each sampling site is provided in Fig. 1 and Table S1. The volume of river water passing through the plankton net was recorded using a digital flow meter (438,110, HYDRO-BIOS, Germany). The net was

then rinsed repeatedly with water without microplastics from the outside to the inside until all the particles were collected in glass sample bottles. River water samples were collected and stored in 1,000 mL acid-washed polyethylene bottles, and 1 mL of nitric acid was added to adjust the pH to 1–2 to avoid precipitation and hydrolysis. Three microplastic samples and three river water samples were collected from each sampling site. The river water samples were analyzed for water quality parameters in accordance with Chinese National Certified Reference Environmental quality standards for surface water (GB 3838–2002). The collected samples were stored at 4°C in the dark upon return to the laboratory.

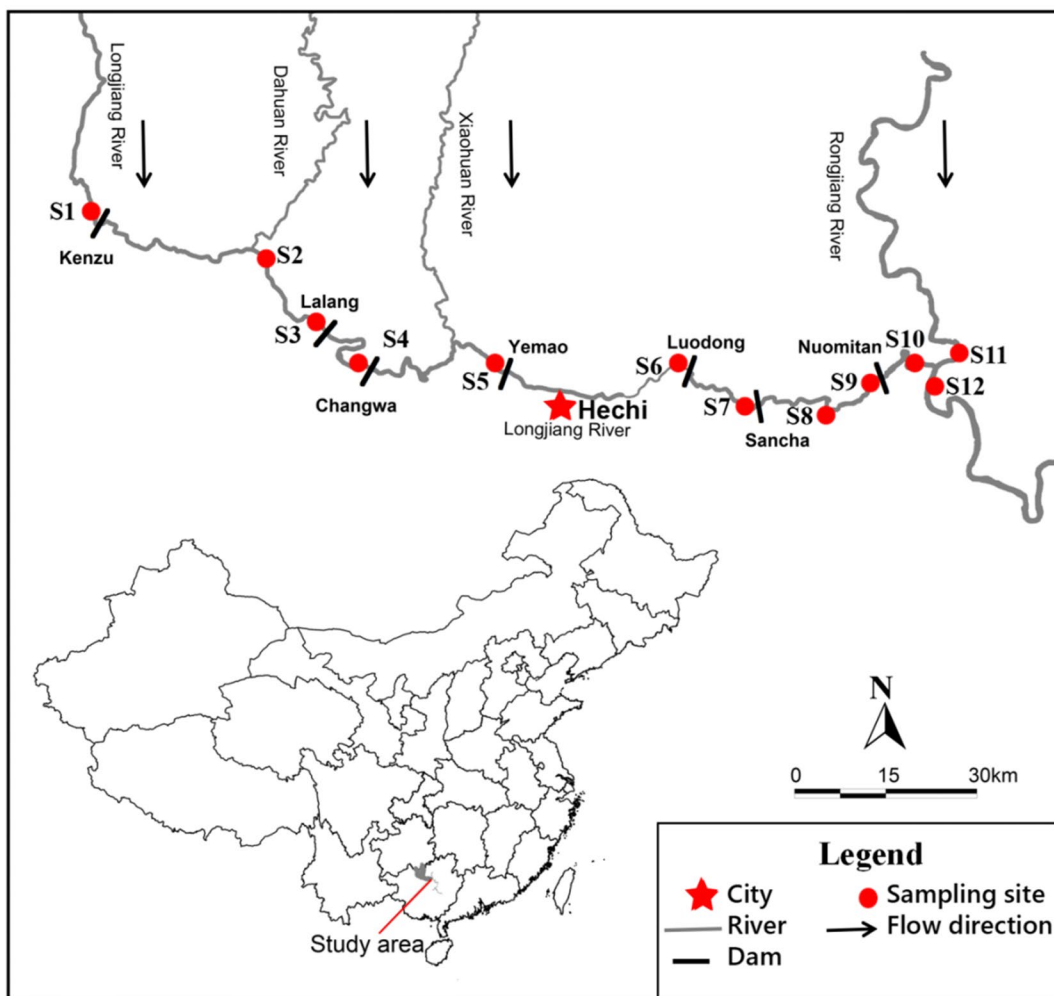


Fig. 1 Sampling sites of MPs in the surface water of the Longjiang River basin, China

2.2 Isolation and Identification of MPs

In the laboratory, water samples for MP analysis were passed through a 30 µm stainless steel sieve to remove large particles of contaminants such as leaves and stones. The MP samples were then rinsed three times with water without microplastics using stainless steel tweezers to avoid errors and ensure that the pretreatment effect was not compromised. All the MP samples were transferred to a 250 ml glass beaker and placed in a vacuum drying oven at 60 °C for 24 h until the volume of the solution was less than 10 ml. Subsequently, 20 ml of ferrous sulfate solution (FeSO₄, 0.05 M) and 20 ml of hydrogen peroxide solution (30%, H₂O₂) were added to the MP samples, which were subsequently placed in a cooling water circulation device. After reacting for 24 h at room temperature, the samples were filtered through a polycarbonate microporous membrane with a pore size of 10 µm. The beakers were then rinsed three times with water without microplastics, after which the rinsing solution was filtered. All the MP samples on the membrane were gently transferred to a separating funnel using a stainless steel scraper, and 50 ml of saturated ZnCl₂ solution (1.5 g/cm³) was added for flotation. The MP samples were fully shaken and left for 2 h before being filtered through polycarbonate microporous filter membranes. These membranes were subsequently placed in a glass Petri dish to dry and await further identification.

The size, appearance, and shape of the MPs were examined using a Fourier transform infrared microscope (Microscope Spotlight 200i, PerkinElmer). The polymer characteristics of the MPs were identified through attenuated total reflection Fourier transform infrared spectroscopy (ATR-FTIR, PerkinElmer Spotlight 200i, PerkinElmer) at specific wavelengths (600–4000 cm⁻¹), resolutions (4 cm⁻¹), and numbers of scans (8 times). Due to limitations of the ATR-FTIR instrument, MPs smaller than 30 µm were not recorded because they were difficult to identify. Components with a spectral match of > 70% were accepted as MPs (Yan et al., 2019).

2.3 Quality Control

The entire experimental procedure was carried out in a clean laboratory. To ensure the cleanliness of the experimental area, the investigators wore cotton lab

coats throughout the operation, avoided polyester type lab coats and donned nitrile gloves. All the stainless steel sieves, beakers, filters, and other instruments were rinsed three times with water without microplastics prior to the commencement of the experiment. During the experimental process, no plastic products were utilized as equipment or consumables. The experiments were executed in strict adherence to the operation specifications, and the samples were promptly wiped with anhydrous ethanol. Upon intermission of the experiment, the containers were sealed with aluminum foil to prevent any potential errors. To mitigate possible MP contamination during the experiment, three blank control experiments were established to investigate the influence of the operating environment on the experimental outcomes. The control procedure and experimental environment were identical to those used in the conventional experiment. No MPs were detected in the blank control experiment.

2.4 Calculation of MP Abundance Values

The abundance of MPs (items/m³) was calculated using the following formula (1):

$$A = \frac{N}{V} \quad (1)$$

where A represents the abundance of MPs in surface water (items/m³), N is the total number of MP items detected in the sample (items), and V is the total sampling volume (m³).

2.5 MP Risk Assessment

The potential risk of MP pollution in the surface water of the Longjiang River was evaluated using three assessment indicators. The first indicator involved hazard scoring of the chemical characteristics of each MP sample collected at all sampling sites (Lithner et al., 2011). Subsequently, the MP-induced risk index (H) was calculated for each sampling site individually (Xu et al., 2018) using the following formula (2):

$$H = \sum (P_n \times S_n) \quad (2)$$

where H represents the MP-induced risk index, P_n is the percentage of the type of chemical characteristic

of the MPs collected at each sampling site, and S_n is the hazard score of the chemical characteristics of the MP samples.

The second indicator was determined by quantifying the abundance of MPs in the entire study area. The MP abundance at each sampling site in the surface water of the Longjiang River was subsequently utilized spatially to assess the MP pollution load index (PLI_{zone}) for the entire region (Xu et al., 2018). The calculation is outlined in formula (3):

$$CF_i = \frac{C_i}{C_{oi}}$$

$$PLI = \sqrt{CF_i}$$

$$PLI_{zone} = \sqrt[n]{PLI_1 PLI_2 \dots PLI_n} \quad (3)$$

where CF_i represents the MP abundance factor, which is calculated as the ratio of the MP abundance C_i to the minimum MP abundance C_{oi} at each sampling site. In this study, the lowest abundance value observed (2.43 items/m^3) was selected as the C_{oi} for the calculation. PLI denotes the pollution load index for a single sampling site, while PLI_{zone} signifies the pollution load index for the entire region.

The third indicator calculates the potential ecological risk factor (E_i) for each polymer at each sampling site utilizing the chemical toxicity factors of polymers proposed by Lithner (Lithner et al., 2011). Subsequently, the potential ecological risk (RI) for the entire range of polymers was derived (Li et al., 2020). The calculation is outlined in formula (4):

$$E_i = T_i \times CF_i$$

$$RI = \sum_{i=1}^n E_i \quad (4)$$

where E_i represents the potential ecological risk factor for a single polymer, T_i denotes the chemical toxicity factor of the polymer as proposed by Lithner (Lithner et al., 2011), CF_i signifies the MP abundance factor, and RI represents the potential ecological risk of the polymer.

2.6 Statistical Analysis

First, this study used the Kolmogorov–Smirnov (KS) test to assess the normality of the datasets. Depending on the outcome of the KS test, we employed the Pearson's correlation to analyze the data followed a normal distribution ($p\text{-value} > 0.05$) and utilized the Spearman's correlation to analyze the data did not follow a normal distribution ($p\text{-value} \leq 0.05$).

The GPS coordinates of the sampling sites were recorded using Omap version 9.1.6. Statistical data analysis was conducted using Microsoft Excel, while Pearson, Spearman, Kruskal–Wallis H, independent sample T test, and systematic cluster analysis were performed on the MP pollution distribution using SPSS version 26.0 (IBM). The MP pollution distribution characteristics were mapped using OriginPro version 2018C.

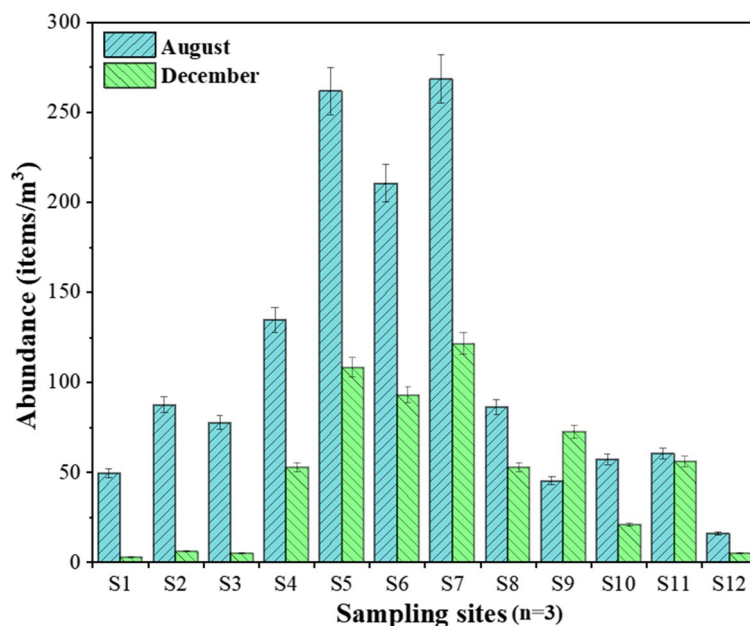
3 Results

3.1 Abundance Characteristics and Source Analysis of MPs

In this study, the abundance of MPs in the surface water of the Longjiang River was investigated at 12 sampling sites in August and December of 2020. A total of 259 MP items were detected in August, with an abundance ranging from 15.61 ± 0.78 to $268.33 \pm 13.42 \text{ items/m}^3$, resulting in an average abundance of $112.60 \pm 5.63 \text{ items/m}^3$. Similarly, 94 MP items were detected in December, with an abundance ranging from 2.43 ± 0.12 to $121.33 \pm 6.07 \text{ items/m}^3$, yielding an average abundance of $49.34 \pm 2.47 \text{ items/m}^3$. The results are presented in Fig. 2.

In August and December, the sites with the highest MP abundances in the surface waters of the Longjiang River were located at the Sancha Hydropower Station (S7). Furthermore, the MP abundances at Yemao Hydropower Station (S5), Luodong Base Wharf (S6), and Sancha Hydropower Station (S7) were greater than those at the other sites. This may be due to frequent human activities in Yizhou District and Liucheng County, as well as the fact that MPs are easily trapped in downstream hydropower stations, which could also be possible reasons for the higher MP abundance at these three sampling sites. The

Fig. 2 Abundance of MPs in surface water in August and December in the Longjiang River basin, China



lowest MP abundance in August was observed in the Liujiang mainstream (S12, 15.61 items/m³), possibly due to the dilution of MPs after the confluence of the Longjiang River and Rongjiang River. In December, the lowest MP abundance was found at Kenzu Hydropower Station (S1, 2.43 items/m³), which was lower than that in August (49.08 items/m³). The upstream region of the Kenzu Hydropower Station is the Hechi Small Three Gorges Scenic Spot, and during the peak tourist season in August, vehicle tire wear and plastic waste from human activities may exacerbate MP pollution levels. However, during both sampling periods, the MP pollution level at Kenzu Hydropower Station was relatively low. This could be attributed to the fact that the upstream area is mostly mountainous and less affected by human activities and industrial pollution.

In order to better understand the differences in MPs pollution between regions with varying economic levels in China, we compared the MPs pollution in the less economically developed Longjiang area with that in the surface water of the Liaohe River conservation area in northern China, which is also economically underdeveloped; with that in the urban surface water of Nanning City's Yongjiang River in southern China, which is relatively more developed; with that in the surface water of semi-enclosed park built along the river in Guilin City, where the service industry is relatively developed; and with that in the

economically developed Pearl River urban area, Pearl River Estuary, and Yangtze River Estuary in southern China (Table S4). Our results showed that the abundance of MPs in the surface waters of the Longjiang River was similar to the average abundance (110 ± 40 items/m³) in the Liaohe River Protection Area (Gong et al., 2022). These values were lower than those in the park waters of Guilin city (104.67–674.44 items/m³) (Li et al., 2022) and the Yongjiang River (2345 ± 1858 items/m³) (Zhang et al., 2020). Furthermore, the abundance was lower than that in the Pearl River urban area of Guangzhou (2724 items/m³) (Lin et al., 2018), the Pearl River Estuary (8902 items/m³) (Yan et al., 2019), and the Yangtze River Estuary (7150 ± 2520 items/m³) (Wu et al., 2022). We also compared the MPs pollution between China and other regions of the world (Table S5), and the results showed that the abundance of MPs in surface waters across different economic levels in China is significantly higher than that in surface waters in other regions of the world.. The large variations in MP abundance may be attributed to differences in pollution levels across different regions. Areas with denser populations and more developed industrial zones tend to have more severe MP pollution due to human activities, industrial discharge, and domestic wastewater discharge. In contrast, the production patterns around the Liaohe River and Longjiang River are

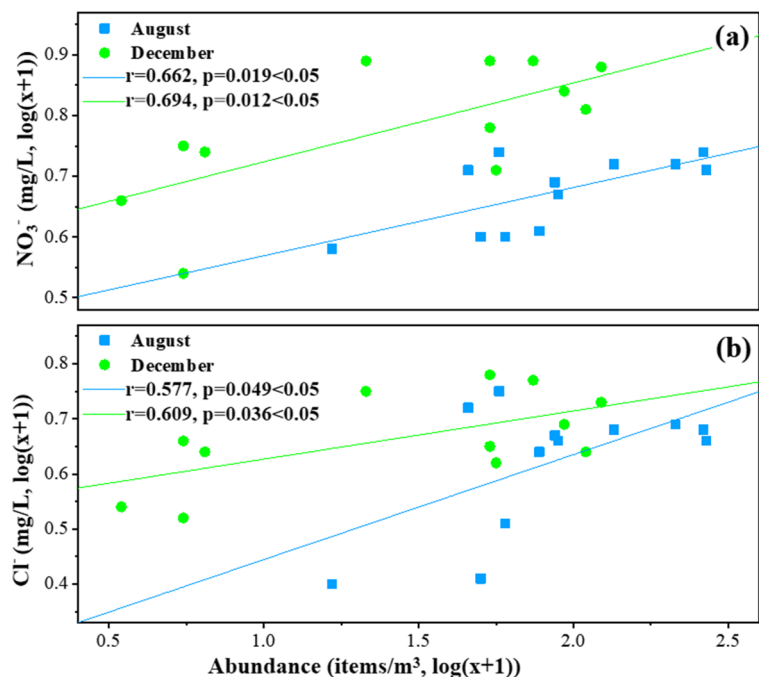
primarily agricultural, with fewer industrial production areas, which may explain the lower levels of MP pollution observed. On the other hand, discrepancies in sampling methods, sample volumes, and matching rates of selected IR spectra could also contribute to differences in MP abundance estimates. Smaller sample sizes and lower matching rates of selected IR spectra may lead to overestimation of MP abundance.

There was a significant difference in MP abundance between August and December (Spearman, $r=0.630, p=0.028 < 0.05$), indicating that hydrological seasonality impacted MP abundance. Studies have shown that the release of MPs from human activities and industrial emissions into the air and surface environment (Abbasi et al., 2019; Liu et al., 2019) can accelerate and concentrate into rivers during the rainy season (Dris et al., 2016), which may explain why most sampling sites in the Longjiang River had higher MP abundances in August than in December. Furthermore, there was no significant correlation between MP abundance in August or December and the distance of each sampling site from the nearest town center (Spearman, $r=0.224, p=0.484 > 0.05$ and $r=0.077, p=0.812 > 0.05$, respectively). This result was consistent with the findings of a study on MP pollution in the Liaohe River protected area (Gong et al., 2022), while some studies have suggested that

MP pollution levels are related to the distance of sampling sites from town centers (Eriksen et al., 2013; Xiong et al., 2018). Therefore, the distance of sampling sites from town centers is not a major factor determining MP abundance in the surface water of the Longjiang River.

To gain a deeper understanding of the potential sources of MP pollution in the Longjiang River, we conducted a correlation analysis between MP abundance and water quality indicators (pH, conductivity, dissolved oxygen, turbidity, NO_3^- and Cl^-) during the same period (Table S2, S3). The results revealed significant correlations between MP abundance in August and December and NO_3^- (Pearson, $r=0.662, p=0.019 < 0.05$ and $r=0.694, p=0.012 < 0.05$, respectively) and Cl^- (Pearson, $r=0.577, p=0.049 < 0.05$ and $r=0.609, p=0.036 < 0.05$, respectively), as illustrated in Fig. 3(a, b). The Longjiang River basin is characterized by advanced agriculture, with crops such as sugarcane and vegetables demanding not only high usage of agricultural films but also nitrogen and potassium fertilizers, leading to extensive application of agricultural films and fertilizers. Agricultural films can effectively provide heat preservation and moisture retention, thereby enhancing crop yields (Liu et al., 2017). The concentrations of NO_3^- and Cl^- may be

Fig. 3 Correlations between the abundance of MPs and NO_3^- (a) and Cl^- (b) in the surface water of the Longjiang River in August and December



influenced by chloride-containing fertilizers (such as potassium chloride and ammonium chloride). Chlorine-containing fertilizers not only effectively enhance soil fertility but also effectively inhibit the concentration of NO_3^- (Vieira Megda et al., 2014). The utilization of ammonium chloride fertilizer offers an effective nitrogen source for the growth of crops such as sugarcane and vegetables and vegetables (Yang et al., 2021) in the Longjiang River basin. In this study, the widespread use of agricultural films and fertilizers may have contributed to the significant correlation between MP abundance and NO_3^- and Cl^- concentrations.

3.2 Physical and Chemical Property Characteristics of MPs and Source Analysis

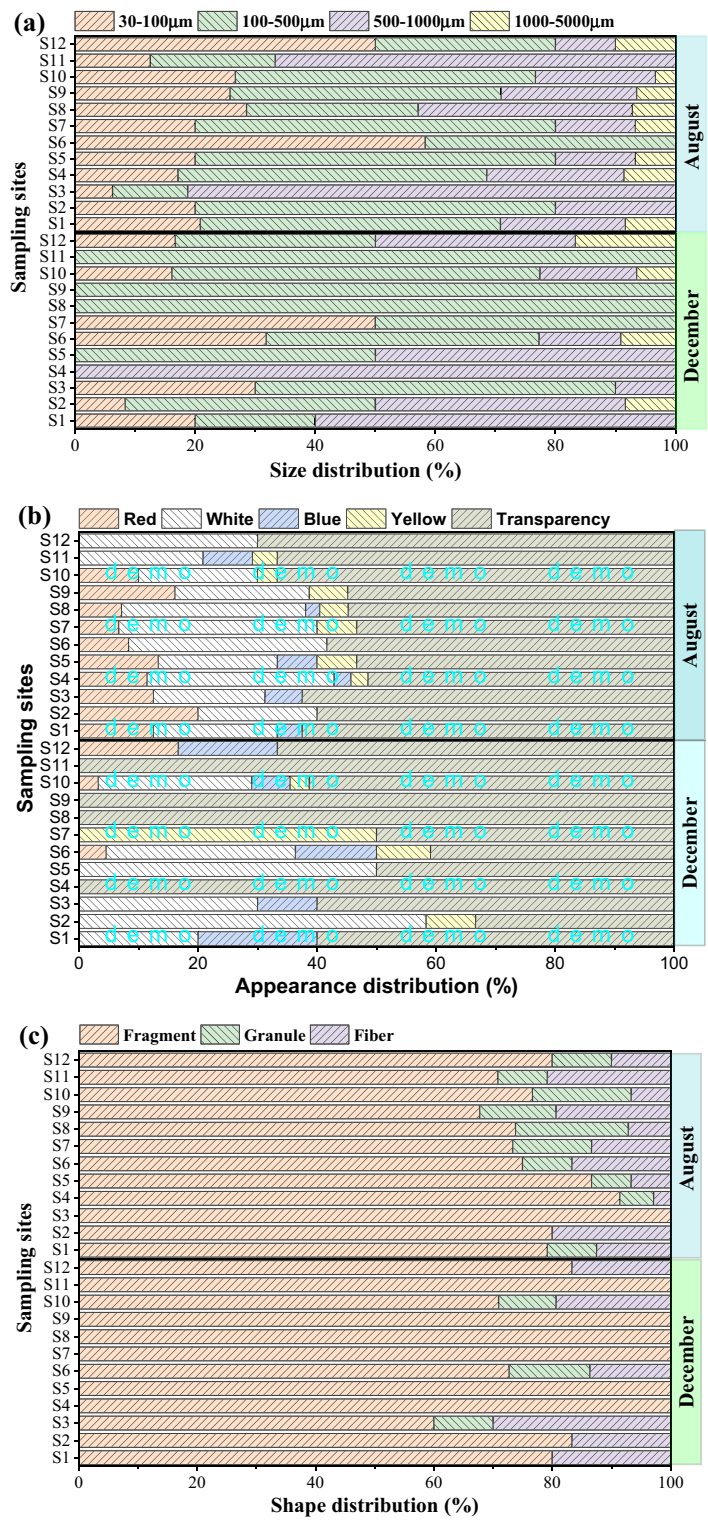
In this study, the physical and chemical properties of the MPs at the sampling sites in the Longjiang River surface water were statistically analyzed for August and December.

The detected MP particles in this study were mostly classified into four categories based on their diameter (30–100 μm , 100–500 μm , 500–1000 μm and 1000–5000 μm), with the longest edge being counted. The spatial and temporal distributions of the MP particle diameter in the Longjiang River surface water are shown in Fig. 4(a). During the wet season (August) and dry season (December), the MP particle diameters were distributed mostly between 100 and 500 μm (42.51% and 55.15%, respectively) and 500 and 1000 μm (27.21% and 27.06%, respectively); the MP samples with a diameter less than 1000 μm accounted for 95.24% and 96.62% in August and December, respectively, of the total. This result indicated that the MP particle diameters at the different sampling sites in August and December were mostly smaller than those in July, while larger MP particles accounted for a relatively small proportion of the total MP particles. The proportion of MPs with a diameter less than 1000 μm in this study was significantly greater than that in the Liaohe Conservation Area (38%) (Gong et al., 2022), Yongjiang Urban Area (25.0%–43.3%) (Zhang et al., 2020), Yangtze River (26.25%) (Wu et al., 2022) and Pearl River (44.8%) (Lin et al., 2018). This is partly due to differences in detection methods, as they did not detect all suspected MPs but randomly detected some suspected MP particles, which could have resulted in the potential

omission of smaller MPs. The smaller particle sizes of secondary MPs may be derived from the weathering of larger MP particles (Li et al., 2022), as shown in Fig. S1a, c, d, and e. There were obvious cracks and fracture marks on the MP surfaces, indicating that MPs can be decomposed into more and smaller-sized particles during transmission due to physical, chemical, and biological factors (Wang et al., 2021a). The smaller the diameter of the MPs is, the greater their specific surface area is, which not only enables them to adsorb pollutants in the aquatic environment but also causes them to be more easily mistakenly consumed by aquatic organisms, causing greater ecological harm through the food chain (Zhou et al., 2022). Considering the crucial impact of MP particle size on the ecological environment and to better understand the temporal and spatial distribution of MP particle size in August and December, PCA was conducted for the MP particle size in the Longjiang River surface water from August and December, as shown in Fig. S2 (a, b). The first principal component contributed 56.1% and 47.2% of the total in August and December, respectively; the major particle sizes associated with the first principal component were 100–500 μm ; the second principal component contributed 24.8% and 32.1% in August and December, respectively; and the major particle sizes associated with the second principal component were 500–1000 μm . The cumulative values of both principal component types with particle sizes of 100–500 μm and 500–1000 μm exceeded 79.3%, indicating that the results of principal component analysis are meaningful and that the distribution of MP particle sizes remains relatively stable with changes in the hydrological period, with smaller-sized MPs dominating. With extensive research on MPs, further research should be conducted for the ecological impacts and health issues caused by extremely small MPs.

The appearance of the MP samples can be mostly classified into five categories: Transparent, white, blue, yellow, and red. The spatial and temporal distributions of MP appearance in Longjiang's surface water are depicted in Fig. 4(b). In August and December, the proportion of transparent MPs was the highest, accounting for 59.53% and 68.52%, respectively. White MPs were the second most abundant, with proportions of 25.17% and 18.00% in August and December, respectively, while blue, yellow, and red MPs accounted for only a minor portion. In the

Fig. 4 Particle size distribution (A), Appearance distribution (B) and shape distribution (C) of MPs in the surface water of the Longjiang River in August and December



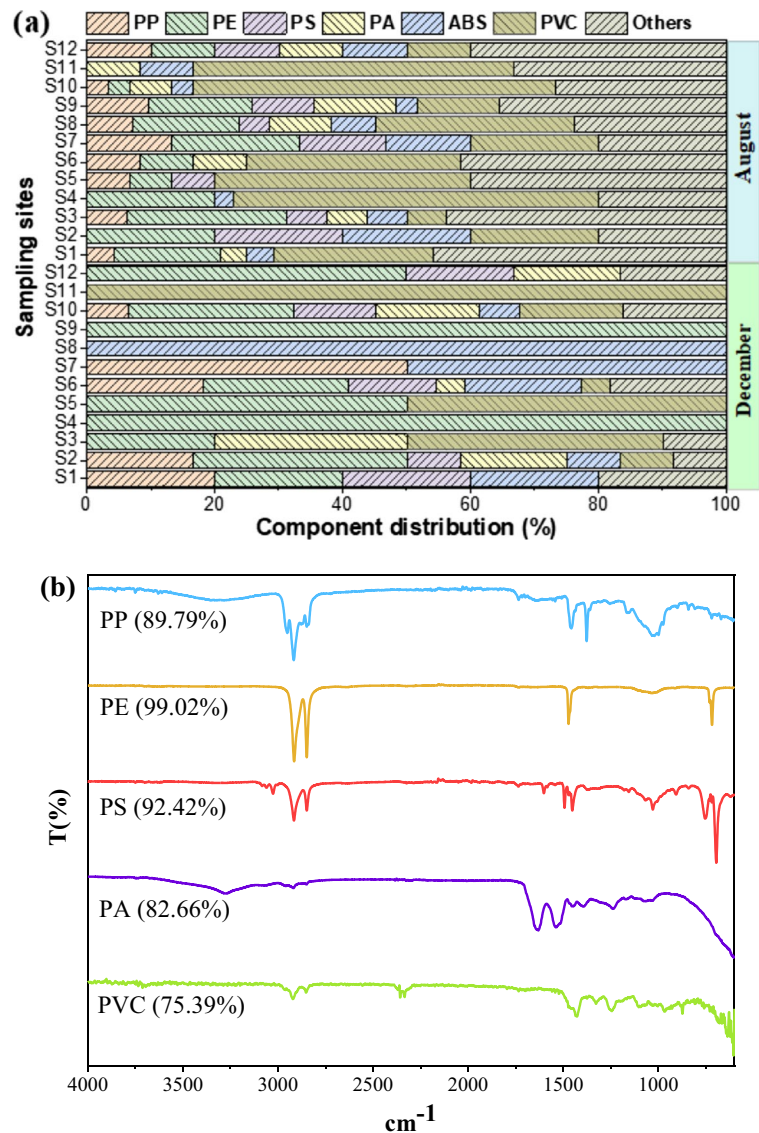
economically underdeveloped Liaohe River, fiber-like MPs were predominantly detected in blue (43.89%) and black (29.4%) (Gong et al., 2022), while white (11.3%) and transparent (1.8%) MPs accounted for a smaller proportion of the total MPs. Conversely, in the economically developed downstream Pearl River urban area, most of the MPs detected were white (65.5%) (Lin et al., 2018). At the mouth of the Pearl River, blue (38%) and transparent (37%) MPs were prevalent, while in the coastal areas of the Pearl River Delta (Yan et al., 2019), transparent (62.5%) and blue (20.07%) MPs were more common (Li et al., 2021b). The results suggested that differences in polymer composition and detection methods between economically developed and underdeveloped regions may contribute to the observed appearance variations in MPs (Table S4). In this study, changes in hydrological period influenced the color of the MPs; for instance, only transparent MPs were detected at sites S4, S8, S9, and S11 in December, while at least two different colored MPs were found in August. Since the appearance of MP samples can partially represent different sources of pollution (Li et al., 2021a) and because MPs may fade during dissolution or transmission between land and water bodies (Wang et al., 2021a), it is possible that variations in pollution sources, dissolution methods, and hydrological periods jointly contribute to the differences in MP appearance observed in the surface waters of the Longjiang River.

The shapes of the MP samples can be mostly classified into three categories: Fragments, granules, and fibers. The spatial and temporal distributions of MP shapes in the surface waters of the Longjiang River are depicted in Fig. 4(c). In August and December, fragmented MPs accounted for the highest proportions at 79.55% and 87.53%, respectively. These were followed by fiber-like MPs at 11.34% and 9.69% in August and December, respectively, while granule-shaped MPs had the lowest proportions at 9.11% and 2.78%, respectively. The proportion of fragmented MPs in the surface waters of the Longjiang River was greater than that in the Liaohe Conservation area (7.24%) (Gong et al., 2022), the Yongjiang River (13.8%) (Zhang et al., 2020), the Guilin City Park water bodies (54.09%) (Li et al., 2022), the Pearl River urban area (18.9%) (Lin et al., 2018) and the downstream Pearl River estuary (52%) (Yan et al., 2019). In this study, both irregularly shaped films

and nonsignificant fragmented MPs were classified as fragments, contributing to the high proportion of fragmented MPs. The proportion of fiber-like MPs was lower than that in the Liaohe River (91.86%), the Yongjiang River (83.2%), the Guilin Park water bodies (36.2%) and the Pearl River urban area (80.9%) but was slightly greater than that in the downstream Pearl River estuary (7%). These results suggested that differences in pollution sources between different regions may lead to variations in MP shapes. From an economic development perspective, regions with varying industrial structures lead to variations in MP types. Human activities in economically advanced areas also exert greater impacts on the quantity of MPs. In terms of agricultural typology, the regions surrounding the Longjiang River are predominantly agricultural, and the utilization of agricultural films may contribute to the prevalence of fragmented MPs. The results also showed disparities in MP shapes across diverse hydrological periods. For example, fragmented MPs were detected at sites S4, S5, S7, S8, S9, and S11 in December, whereas other sites exhibited at least two distinct shapes of MPs in August. This suggested that the sources of MP pollution may vary across different hydrological periods and that alterations in hydrological conditions have a discernible influence on the shape of MPs.

A total of 9 chemical features were identified at the 12 sampling sites. The chemical composition distribution and infrared spectroscopy data of the MPs in Longjiang's surface water are presented in Fig. 5(a, b). The predominant MPs found were polypropylene (PP), polyethylene (PE), polystyrene (PS), polyamide (PA), acrylonitrile butadiene styrene (ABS), and polyvinyl chloride (PVC). PE and PVC were the dominant MPs in August and December, with percentages of 13.57% and 30.19%, respectively, in August and 35.16% and 18.25%, respectively, in December. The PE and PVC fragments were primarily transparent, while the PS and PA fibers were mostly blue and white. The PP particles were predominantly black. Artificial silk (56.11%) and PET (27.15%) were detected in greater quantities in the Liaohe River than in the other rivers (Gong et al., 2022). In the Yongjiang River, PE (33%) and PET (21%) were more frequently detected than in the other rivers (Zhang et al., 2020). In Guilin's park water bodies, PE (84%) and PET (16%) were present in greater proportions (Li et al., 2022), while more PP and PE were detected in

Fig. 5 Chemical distribution (a) and infrared spectra (b) of MPs in the surface water of the Longjiang River in August and December



the Pearl River urban area (Lin et al., 2018) and the Yangtze River estuary (Xu et al., 2018). These findings suggested that there are variations in the types of MP pollution in water bodies across different regions, which may be attributed to differences in the sources of MPs. Economically developed areas are likely to be greatly influenced by industrial activities, with the emissions of PET commonly used in the textile industry, PP commonly used in the electronics industry, and PE commonly used in daily life, potentially leading to higher pollution levels (Table S3). Economically developed regions may be most affected by the industrial production and human activity intensity,

while regions with a relatively well-developed service industry may be impacted primarily by human activity intensity. Conversely, economically underdeveloped regions may exhibit varying degrees of pollution due to differences in local agricultural production. Evidently, MP pollution is closely related to regional economic development and human activities.

To gain a better understanding of the sources of MPs in Longjiang's surface water, we conducted a systematic cluster analysis on the chemical composition of MPs detected in August and December. The results are presented in Fig. S3 (a, b). Our findings revealed that among all the sampling sites, PVC from

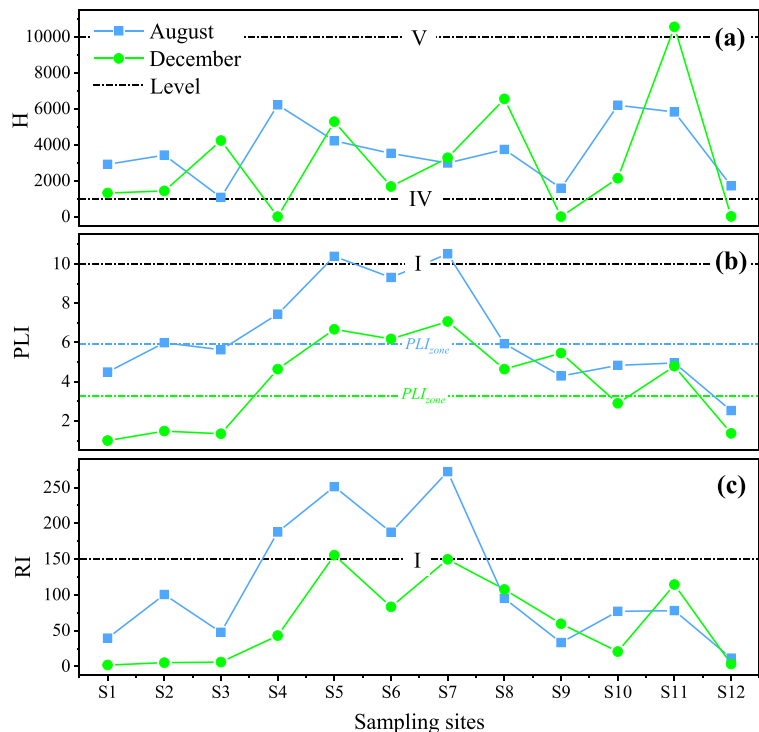
MPs in the Longjiang River surface water was the most abundant MP in August. The polymer compositions detected at seven sampling sites (S1, S5, S6, S4, S8, S10, and S11) were found to be most similar, with PVC being the dominant component. Additionally, a significant negative correlation was detected between the PS and PVC at the same sampling sites through Spearman correlation analysis (*Spearman*, $p=0.010 < 0.05$). This may be attributed to the fact that PS is primarily used in daily life items such as food containers and stationery accessories, while PVC is predominantly used in agricultural areas for agricultural film applications. Given that the Longjiang Basin is primarily an agricultural region, the use of PVC agricultural films may result in more PVC fragments being collected in the Longjiang River during the flood season due to surface runoff. In December, the PE and PVC polymers were clustered into two major groups of MPs found in the surface water of the Longjiang River. The polymer compositions detected at sampling sites S3, S11, and S5 were most similar, with PVC being the predominant component. In contrast, at sampling sites S2, S4, S9, S10, and S12, PE dominated the polymer compositions. This difference could be attributed to the decrease in rainfall

during the dry season, which may have hindered the prompt collection of agricultural PVC films in rivers and surface runoff in agricultural areas. As a result, there was an increase in the proportion of PEs generated from human activities. The results also showed variations in the types of MPs present in August and December due to changes in hydrological periods. These changes affected the abundance, size, color, and shape of the MPs. Furthermore, a significant negative correlation was found between PEs and ABSs at the same sampling sites (*Spearman*, $p=0.040 < 0.05$). This indicated that economically underdeveloped regions are more heavily polluted by PEs generated from human activities, while regions affected by electronic industrial products are less polluted by ABSs. PVC dominated at both the S5 and S11 sampling sites in August and December, which further indicated that the variation in hydrological period did not significantly affect PVC pollution at these two sites.

3.3 Risk Assessment of MP Contamination

The standard levels of H , PLI_{zone} and RI are presented in Table S4 (Li et al., 2020; Lithner et al., 2011). As shown in Fig. 6(a), the H values of MP pollution

Fig. 6 H (a), PLI (b) and RI (c) values of MPs in surface water of Longjiang River in August and December



at most sampling sites in the surface water of the Longjiang River were high in August and December, indicating that MP pollution should be considered seriously. Specifically, the H ranged from 1076.6 to 6218.5 for all sampling sites in the Longjiang River in August, with a pollution risk level of IV, which could cause acute toxicity, respiratory and skin allergies, etc. (Table S4). In December, H ranged from 11.0 to 10,551.0 for all the sampling sites. The highest MP pollution risk level (V) was found at S11, which could cause carcinogenicity, reproductive toxicity, and bioaccumulation in humans. The lowest levels (II) were observed at S4, S9, and S12, which could cause skin and eye irritation, toxicity to specific organs, and harm to the aquatic environment. The pollution levels at the remaining sampling sites were all IV. The results showed that changes in hydrological periods only slightly impacted the MP pollution risk index, primarily due to differences in the chemical composition and content of MPs. One study revealed that high chemical toxicity of MP particles results in high environmental risk (Peng et al., 2018). The most harmful component detected in August and December was PVC, with a hazard score of 10,551 (Lithner et al., 2011), which is also an important reason for the high MP pollution risk index in the surface water of the Longjiang River. However, no polymers with high hazard scores were detected in the water bodies of the Liaohe Conservation (Gong et al., 2022) or Guilin City Park (Li et al., 2022), both of which had pollution risk indices of I. Additionally, PVC was also detected in the Pearl River (Yan et al., 2019) and the Yangtze River (Xu et al., 2018), which had pollution risk indices of III in the Yangtze River estuary. The pollution risk index of MPs is inextricably related to the type and abundance of MPs, and higher hazard scores of MP emissions lead to higher pollution levels.

As depicted in Fig. 6(b), the PLI_{zone} of the Longjiang River exhibited a greater value in August (5.90) than in December (3.23). The overall pollution level of the Longjiang River was classified as I. In August, the PLI ranged from 2.53 to 10.51 at all sampling sites, except S5 and S7, which had a pollution level of II, while all the other sites had a pollution level of I. A higher MP abundance corresponded to a higher pollution level. In December, the PLI ranged from 1.00 to 7.07 at all sampling sites, with a pollution level of I for all sites. The results indicated that changes in

hydrological periods impact the PLI . During high-flow periods, surface runoff and other factors contribute to the increase in MP pollution. The PLI in the surface waters of the Longjiang River, Liaohe River (Gong et al., 2022) and Guilin Park water bodies (Li et al., 2022) are relatively low, while the PLI is generally greater in the coastal areas of the Yangtze River Estuary (Xu et al., 2018) and Pearl River Estuary (Li et al., 2021b). This suggests that there is a direct correlation between the regional economic development level and the MP pollution load. Although the MP pollution load in the surface water of the Longjiang River is relatively low, the high risk index is due to the presence of harmful types of discharged MPs, indicating that MP pollution in less developed areas should not be underestimated.

MP pollution poses potential harm to ecosystems. In addition to assessing MP pollution using H and the PLI , it is necessary to evaluate the potential RI . As shown in Fig. 6(c), the RI in the Longjiang River is classified as level I. In August, the RI ranged from 11.56 to 272.35 at all sampling sites, and the pollution levels were I at all sampling sites except for S4, S5, S6 and S7, which had pollution levels of II. In December, the RI ranged from 2.00 to 155.54 at all sampling sites, except S5, which had a pollution level of II, while all the other sites had a pollution level of I. The results indicated that sampling sites with higher emissions of PVC from agricultural films have greater ecological risk. This suggested that the higher the toxicity coefficient and abundance of MPs are, the greater the corresponding potential ecological risk.

4 Conclusion

MPs were detected at all sampling sites in August and December in the surface water of the Longjiang River. The data indicated that variations in hydrological periods significantly impact MP abundance. The abundance of MPs ranged from 15.61–268.33 items/m³ and 2.43–121.33 items/m³ in August and December, respectively. Nine polymers were detected through attenuated total reflection Fourier transform infrared spectroscopy, and the two major chemical components were PE and PVC. Variations in hydrological periods and different sources of pollution jointly influenced the differences in MP composition proportions as well as slight variations

in particle size, appearance, and shape. The granule sizes of the MPs mainly ranged from 100–500 µm, with a predominantly transparent color and fragment shape. Based on the pollution risk index derived from the chemical composition of MPs, the pollution risk in the surface water of the Longjiang River is primarily classified as IV. Considering the pollution load index based on MP abundance, the MP pollution risk load for the surface water of the Longjiang River is classified as level I. The potential ecological risk of MP pollution in the surface water of the Longjiang River is mainly level I, indicating a relatively low level of contamination. By comparing these regions with economically developed regions, it can be concluded that human activities and industrial production critically influence MP abundance and pollution risk. Economically underdeveloped regions with agricultural-based economies also face MP pollution risks due to the higher proportion of PE and PVC fragments resulting from using agricultural films. Therefore, it is crucial to reduce the usage of high-hazard scoring plastic products, enhance the recycling of plastic products, and clean up waste plastic garbage.

Acknowledgements This work was financially supported by Development Program of Guangdong Province (2020B1111380003) and National Natural Science Foundation of China (41977353). We also would like to thank Cheng Qian (PerkinElmer, Inc.) for providing MPs testing equipment and technical support.

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Funding Development Program of Guangdong Province, 2020B1111380003, Chang Liu, National Natural Science Foundation of China, 41977353, Qianli Ma

Data Availability The authors declare that the data supporting the findings of this study are available within the paper and its Supplementary Information files. Should any raw data files be needed in another format they are available from the corresponding author upon reasonable request. Source data are provided with this paper.

Declarations

Ethical approval This study did not involve human or animal subjects, and thus, no ethical approval was required. The study protocol adhered to the guidelines established by the journal.

Consent to Participate All authors agreed with the content and that all gave explicit consent to submit and that they obtained consent from the responsible authorities at the institute/organization where the work has been carried out, **before** the work is submitted.

Consent to Publish All authors have approved to submit this manuscript to Environmental Science and Pollution Research, and approve the manuscript to be published.

Competing Interests The authors have no relevant financial or non-financial interests to disclose.

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