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Distribution Characteristics and Sources of Microplastics in Inland Wetland Ecosystem Soils

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Abstract: Microplastic (MP) pollution, an emerging global change factor, disturbs the ecosystem functioning. Inland wetlands, providing important ecosystem services, might be an important sink for MPs. Understanding the distribution, source, and fate of MPs in inland wetland ecosystems is a prerequisite for developing an effective management strategy. Here, different types of inland wetlands, including the river wetland, constructed wetland, and lake wetland, were selected to explore the pollution patterns of MPs therein. Results showed that the abundance of MPs in wetland soil ranges from 532 to 4309 items/kg. Transparent, fibers, and polyethylene terephthalate were the most common color, shape, and polymer type of MPs, respectively. The constructed wetland in this study did not significantly remove MPs. The lake wetland was one of the main sinks for MPs in the inland wetland ecosystem and had accumulated large amounts of MPs. In addition, MP characteristics and cluster analyses showed that aquaculture, agricultural cultivation, and domestic waste were the most important sources of MPs in the study area. The occluded particulate organic carbon content in this study was related to MP abundance. In conclusion, this study reveals the pollution characteristics of MPs in the special inland wetland ecosystem of river-constructed-lake wetlands, which would help to better understand the distribution and source of MPs in inland wetlands and have implications for the subsequent pollution control and ecological restoration of inland wetlands.

Keywords: constructed wetland; distribution characteristics; inland wetland; microplastics; sources

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1. Introduction

Plastics are widely used because of their advantages, such as waterproof insulation, lightweight, and durability [1]. Global production of plastics increased from 2 to 400 million tons between 1950 and 2019 [2,3]. Only 9% of discarded plastic products are recycled, and large amounts of plastic waste enter the natural environment, with the accumulation of plastics in the environment expected to reach 3.1 billion tons by 2050 [4–6]. Plastic particles less than 5 mm in size are identified as microplastics (MPs), including primary and secondary MPs [7]. Primary MPs usually originate from industrial production, such as the production process of detergents, personal care products, and cosmetics [8,9]. Secondary MPs are plastics less than 5 mm in size produced by ultraviolet aging, mechanical wear, and biodegradation of large plastics in the environment, such as microfibers from textile aging, microparticles from tire wear, and microfilms from degradation of agricultural mulch [10].

Oceans are acknowledged as major sinks for MPs and are the most widely studied sites for MPs [11,12]. Many research reports have been published regarding marine MPs [13]. For example, studies of MPs in Malaysian beaches [14], Singapore beaches [15], Qatar's Exclusive Economic Zone seawater [16], South China Sea Zhongsha Atoll seawater [17], Arctic deep-sea sediments [18], and Belgian marine sediments [19]. The MP abundance in terrestrial ecosystems is 4–23 times higher than that in marine ecosystems [20]. This discovery has warranted researchers to shift the focus of their studies to terrestrial ecosystems.

Inland wetlands might be significant repositories for MPs in terrestrial ecosystems, possessing the capacity to capture MPs from both water and atmospheric sources [21]. Domestic and industrial sewage discharges are important sources of MPs in inland wetlands [22]. Landfills are also important reservoirs and disseminators of MPs [23]. Mulch, sludge compost, tires, asphalt, and road marking coatings are also important sources of wetland MPs [24]. Constructed wetlands provide an alternative method of treating wastewater and are often used for the deep treatment of wastewater [25]. Furthermore, the substrate, biofilm, and plants in constructed wetlands can filter MPs [26]. It has been shown that smaller substrate sizes, lower water flow rates, and extended flow paths all contribute to enhanced MP adsorption onto substrates [27]. However, the constructed wetlands not only contribute to the removal of MPs but also are a critical pathway for MPs, including nanoplastics, to enter inland wetlands [28].

As an emerging pollutant, MPs introduce a potential threat to the environment and human health when entering inland wetlands [29,30]. For example, MPs are capable of influencing soil physicochemical properties, including soil porosity, pH, soil moisture, soil organic carbon, and active phosphorus [31,32]. In industrial production, a number of plastic additives are usually used to give desirable properties to plastics, such as lubricants, flame retardants, ultraviolet stabilizers, antioxidants, and plasticizers [33]. Weak bonding between plastic additives and polymers leads to certain toxic additives entering the environment [34]. Moreover, MPs can easily enter organisms through skin contact, air inhalation, and food ingestion and be passed through the food chain, posing a potential threat to aquatic organisms, birds, mammals, and even humans [35,36]. Their toxicity includes induction of oxidative stress, neurotoxicity, DNA damage, growth inhibition, and immune disorders [37]. Furthermore, MPs have a large specific surface area and abundant adsorption sites, so they can adsorb hazardous substances such as organic pollutants, heavy metals, antibiotics, and microorganisms in the environment through electrostatic adsorption, complexation, and hydrogen bonding [38,39]. This adsorption affects the migration of MPs within the ecosystems, leading to more serious complex pollution.

Xinxue River, Xinxue River Constructed Wetland, and Nansi Lake constitute a unique inland wetland ecosystem in northern China. The lake plays a crucial role in water storage in the South-to-North Water Diversion Project and has become a sink for pollutants after a long period of accumulation because the drainage basin does not have access to the sea. The constructed wetland is built at the inlet of the river, which can effectively reduce the pollutants entering the lake. We researched the abundance and characteristics of MPs in this river-constructed-lake wetlands ecosystem to reveal the MP pollution in inland wetland ecosystems. We hypothesized that (1) lake wetlands are one of the main sinks for MPs in inland wetland ecosystems; (2) constructed wetlands can remove MPs; and (3) aquaculture, agricultural cultivation, and domestic waste are the main sources of MPs.

2. Materials and Methods

2.1. Study Sites and Sample Collection

The study site was selected at Nansi Lake, Jining City, Shandong Province, China (Figure S1). Nansi Lake is the largest freshwater lake in North China, and it is where

53 rivers converge, and the basin does not reach the sea [40]. The Xinxue River, one of the primary rivers in Nansi Lake, features the Xinxue River Constructed Wetland situated at its inlet. This wetland has been constructed to effectively enhance the water quality of the river inflow into Nansi Lake and restore the ecological functionality of the lake wetland ecosystem.

To investigate the MPs distribution of the river-constructed-lake wetlands ecosystem, six sampling areas were set up in the upstream (RU) and downstream (RD) of the river, the inlet (CU), middle reaches (CM), and outlet (CD) of the constructed wetland, and the lake wetland(L). Five sampling sites were set up in each sampling area, and the distance between sampling sites was approximately 200 m. Along the bank of the inland wetland, 1 m × 1 m sample squares were set up in the absence of plant growth and at a water depth of 1 m. Soil augers were used to collect 0–10 cm of topsoil. Sampling was conducted using the five-point sampling method, in which five portions of soil were thoroughly mixed and collected as a composite soil sample. A total of 30 samples were collected and stored at 4 °C for further analysis.

2.2. Separation and Extraction of MPs

Thirty samples for the detection of MPs were dried to a constant weight and passed through a 5 mm sieve after removing visible rock, shell, and plant fragments [41]. Specifically, 50 g of soil was placed in a 300 mL conical flask, and 150 mL of saturated $ZnCl_2$ solution (density = 1.6 g/cm^3) was added. The conical flask was sonicated in a CNC ultrasonic cleaner (KQ–700DE) for 20 min to promote soil dispersion and then shaken at 200 r/min for 2 h. Next, a saturated $ZnCl_2$ solution was added to the neck of the conical flask and left to stand. Subsequently, the upper layer of supernatant was then meticulously poured into beakers to reduce the amount of soil particles extracted [42]. The extraction process was repeated a total of three times; then, the extracts were mixed and passed through a 0.45 μm filter membrane. The residue on the membrane was transferred into a conical flask with 30% H_2O_2 and subjected to digestion at 50 °C for a period of 24–72 h to eliminate organic matter. The samples were filtered again, and the membranes carrying the MPs were placed in pre-washed petri dishes to dry naturally and then stored at 4 °C under a glass lid for subsequent analyses.

2.3. Quantitative and Qualitative Analysis of MPs

MPs were quantified using a stereomicroscope (SMZ 18, Nikon Co., Ltd., Tokyo, Japan), where MP samples were identified, photographed, and counted in a field of view ranging from 10× to 135×. MP abundance in soil was measured in terms of items/kg. MPs were then classified by manual observation based on shapes (fibers, fragments, films, and foams), colors (transparent, white, blue, red, yellow, black, and green), and sizes (29–500 μm, 500–1000 μm, 1000–2000 μm, and 2000–5000 μm).

Suspected MPs extracted from soils of different inland wetlands were characterized using Fourier transform micro-infrared spectroscopy (Nicolet iN10, Thermo Fisher Scientific Co., Ltd., Waltham, MA, USA). One hundred and twenty suspected particles were randomly selected from all samples, picked out with stainless steel tweezers under a microscope and transferred to a diamond pressure cell. The μ-FTIR was used under operating conditions of transmission mode, spectral resolution 8 cm^{-1}, detector spectral range 675–4000 cm^{-1} after cooling and 16 scans per acquisition. The infrared spectra obtained from the detection were compared with the standard spectra of plastics, and a match of more than 70% was considered to be MPs; finally, 85.83% of the selected particles were identified as MPs. MP abundance was then recalculated based on the identification results.

2.4. Soil Physicochemical Analysis

Soil moisture (SM, %) and bulk density (BD, g/cm^3) were determined by the ring knife method. Fresh soil was sieved through a 2 mm sieve for the determination of dissolved organic carbon (DOC, mg/g), ammonium nitrogen (NH_4^+-N, mg/kg), nitrate nitrogen (NO_3^--N, mg/kg), and total phosphorus (TP, mg/kg). The remaining soil was air-dried to constant weight at room temperature and passed through a 2 mm sieve or a 0.149 mm sieve to determine other soil physicochemical properties. A total organic carbon analyzer (DDS-307A, Shanghai INESA Instrument Co., Ltd., Shanghai, China) was used for the determination of DOC, a pH meter (PHS-3E, Shanghai INESA Instrument Co., Ltd., Shanghai, China) for the determination of soil pH, and a conductivity meter (DDS-307A, Shanghai INESA Instrument Co., Ltd., Shanghai, China) was used to determine soil electrical conductivity (EC, μS/cm). Cation exchange capacity (CEC, cmol$^+$/kg) was determined by the hexamine cobalt trichloride leaching-spectrophotometric method, and soil texture (clay&silt, %) was determined by a modified pipette method [43]. NH_4^+-N, NO_3^--N, and TP were determined by an automatic sampling continuous flow analyzer (San++, SKALAR, Breda, the Netherlands). Free particulate organic carbon (fPOC, mg/g), occluded particulate organic carbon (oPOC, mg/g), mineral-associated organic carbon (MAOC, mg/g), soil organic carbon (SOC, mg/g), and total nitrogen (TN, mg/g) were determined by an elemental analyzer (Unicube, Elementar, Frankfurt, Germany).

2.5. Statistical Analysis

The abundance and characteristics of MPs were measured using ImageJ (Version 2). A comparison of infrared spectra of suspect particles with standard spectra of plastics using OMNIC (Version 8.2) was used to identify the MPs' polymer types. Similarities between MP characteristics were investigated using cluster analysis to speculate on the origin of MPs. The correlation between MPs and environmental factors was tested by Spearman correlation analysis, principal component analysis (PCA), and regression analysis. Other data analyses were conducted using SPSS (Version 26.0), Origin (Version 2024), ArcGIS (Version 10.6), and Canoco (Version 5).

3. Results

3.1. Abundance and Distribution of MPs

MPs were widely detected in the river-constructed-lake wetlands ecosystem (Figure 1). The abundance of MPs ranged from 532 to 4309 items/kg. Among the sampling areas in the inland wetland, the highest MP abundance was found in L, with its average abundance of 2613 ± 1092 items/kg ($p < 0.05$, Figure 1a). This was followed by RD, CU, RU, CD, and CM, with mean abundances of MPs being 1157 ± 293, 944 ± 274, 909 ± 192, 827 ± 349, and 769 ± 159 items/kg, respectively (Figure 1a).

3.2. Physical Characteristics of MPs

Typical pictures of MPs observed by stereomicroscope and typical infrared spectra identified by μ-FTIR are shown in Figures 2 and S2. The most common color of MPs was transparent, with 53.0%. This was followed by yellow, black, blue, and red with 15.1%, 10.7%, 8.9%, and 8.3%, respectively (Figure 3a). Green and white MPs were very low, with only 2.8% and 1.1%, respectively (Figure 3a).

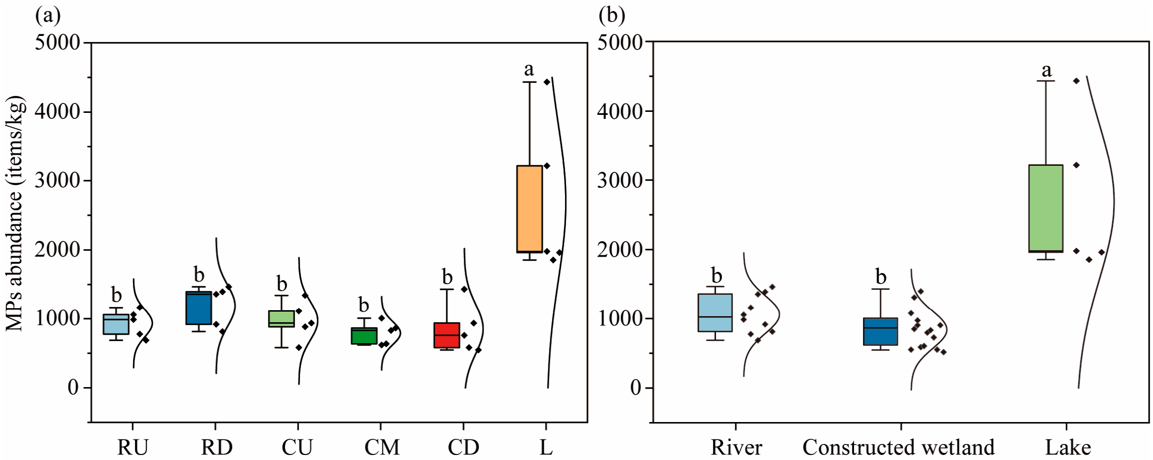

Figure 1. Comparison of MP abundance in different sampling areas (**a**) and different types of inland wetlands (**b**). Different superscript lowercase letters indicate significant differences ($p < 0.05$). RU—river upstream; RD—river downstream; CU—constructed wetland inlet; CM—constructed wetland midstream; CD—constructed wetland outlet; L—lake wetland.

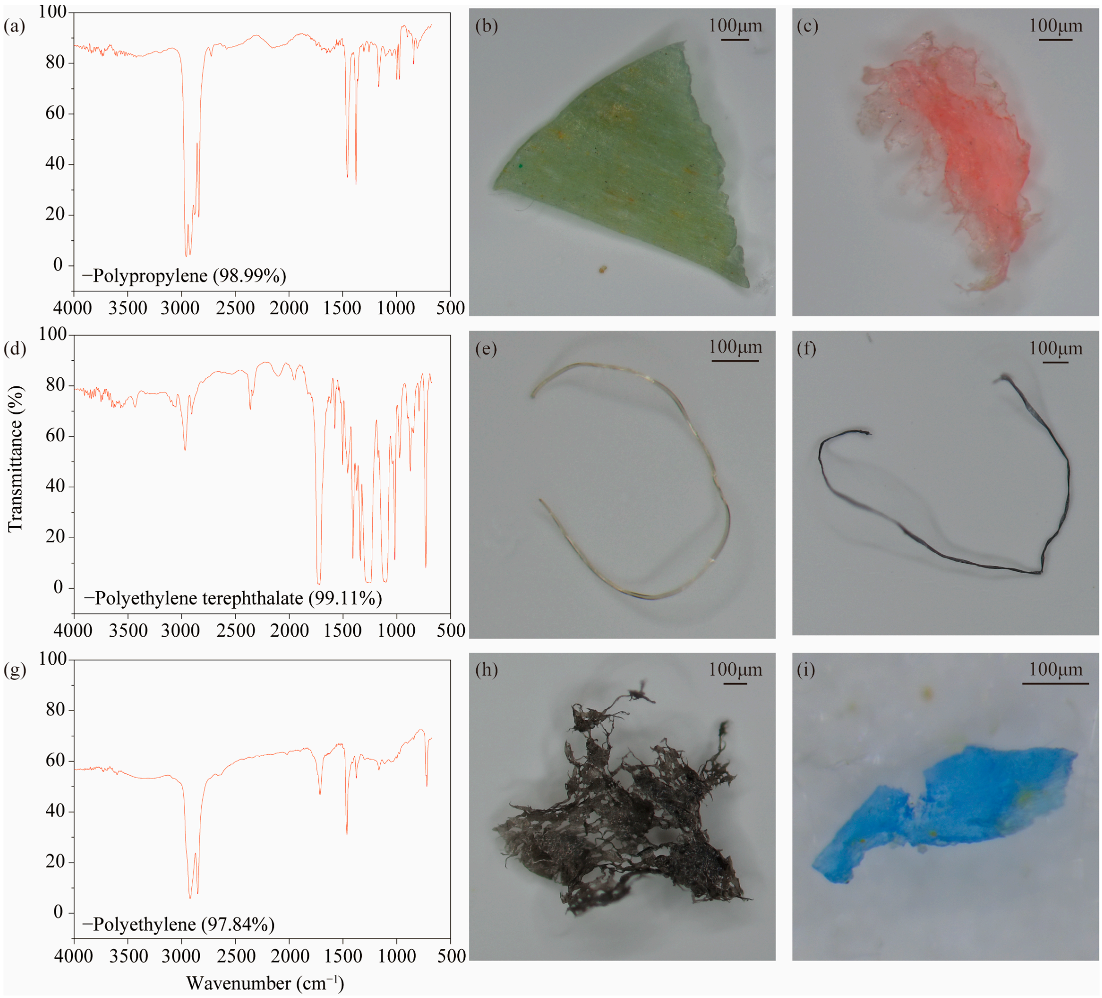

Figure 2. Infrared spectra of typical MPs identified by μ-FTIR, PP (**a**), PET (**d**), and PE (**g**), with percentages in parentheses representing the match of the sample infrared spectra to the standard infrared spectra. Pictures of typical MPs observed under stereomicroscope, fragments (**b**), films (**c**,**i**), fibers (**e**,**f**), and foams (**h**).

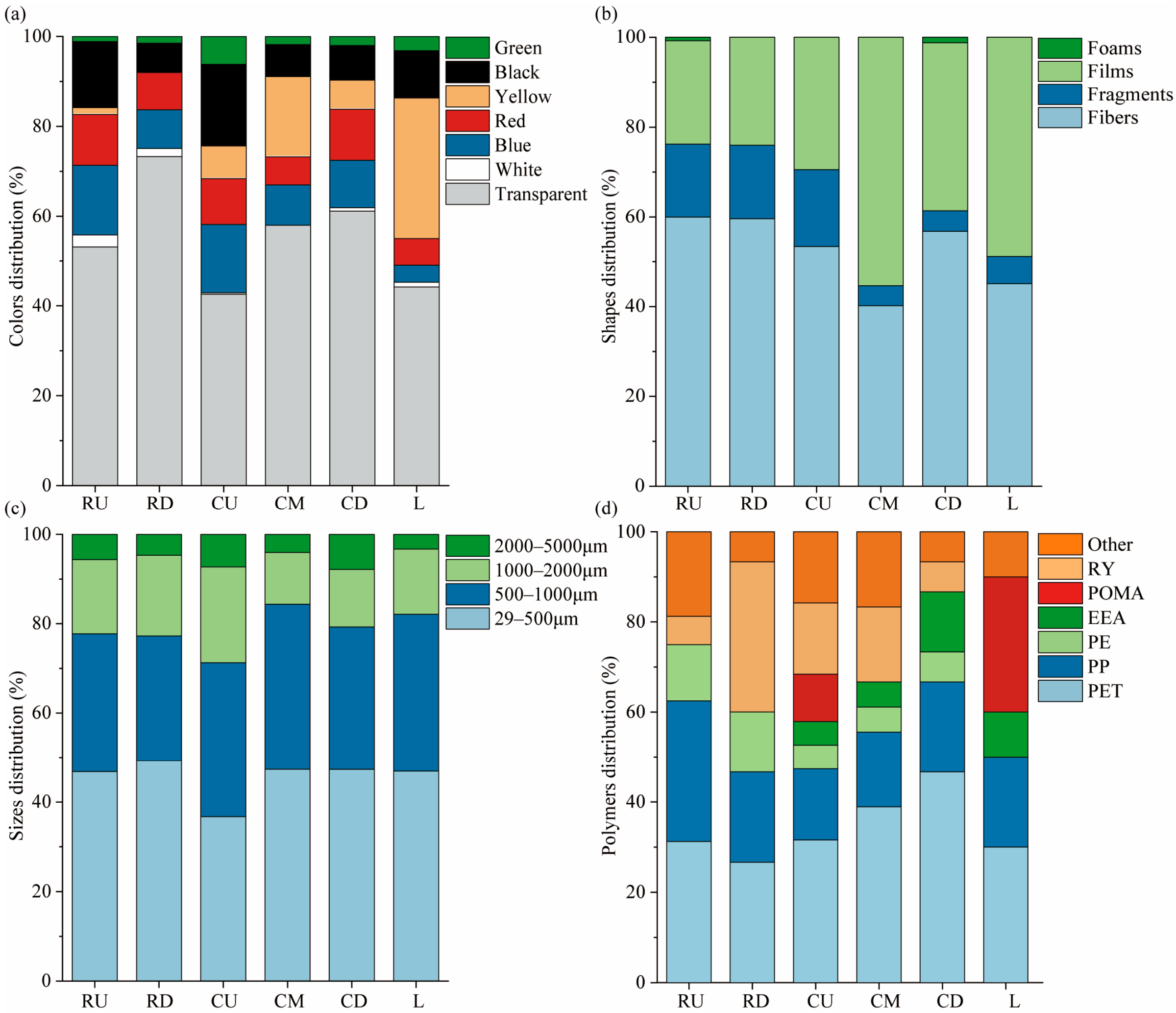

Figure 3. Colors (**a**), shapes (**b**), sizes (**c**), and polymers (**d**) of MPs.

Four shapes were detected in all wetlands soil samples, including fibers (51.2%), films (38.5%), fragments (10.1%), and foams (0.2%) (Figure 3b). The fragments are predominantly found in RU, RD, and CU, while the films are predominantly found in CM, CD, and L (Figure 3b). Fiber abundance was higher in RU and RD associated with fisheries aquaculture activities (Figure 3b).

The abundance of MPs gradually increased with decreasing size (Figure 3c). Among all sampling sites, MP abundance was highest at 29–500 µm, which accounted for 46.0% (Figure 3c). This was followed by MPs in the size ranges of 500–1000 µm, 1000–2000 µm, and 2000–5000 µm, with 33.2%, 15.8%, and 4.9%, respectively (Figure 3c).

Twelve MP types were detected in wetland soils using µ-FTIR, with polyethylene terephthalate (PET, 34.0%) and polypropylene (PP, 20.4%) being the most predominant types, which were widely distributed in the six sampling areas (Figure 3d, Table S1). This was followed by polyethylene (PE), ethylene-ethyl acrylate (EEA), poly (octadecyl methacrylate) (POMA), rayon (RY), and others with 6.8%, 5.8%, 7.8%, 12.6%, and 12.6%, respectively (Figure 3d, Table S1). Specifically, POMA was predominantly distributed in the L, and RY was predominantly distributed in the RD, CU, and CM (Figure 3d).

3.3. The Relationships Between the Characteristics of MPs

By comparing the relationships between MP characteristics, it was found that the colors, sizes, and polymer types showed different distributions in different shapes. A wide range of colors were found in fibers; the most prevalent color was transparent (55.0%), followed by black (17.4%), yellow (12.2%), blue (9.3%), and red (4.8%) (Figure 4a). The prevalent colors of fragments were transparent (53.0%) and blue (22.3%), while for films, the dominant colors were transparent (44.4%), yellow (34.9%), and red (12.4%). The sizes of films and fragments in the three types of wetland soils were generally smaller than those of fibers, suggesting that films and fragments are more susceptible to weathering and fragmentation (Figure 4b). Three main polymers were identified in fibers (PET, PP, and RY) and films (PP, PE, and POMA), respectively (Figure 4c). Foams were minimal in the study area, and only one polymer, PE, was identified, meaning that foams in the study area were black and white PE plastics. Cluster analysis showed that films, fibers, transparent, red, yellow, black, green, and POMA formed one clade due to high similarity, and fragments, blue, and PP formed another clade, with the different clades possibly representing different MPs sources (Figure 4d).

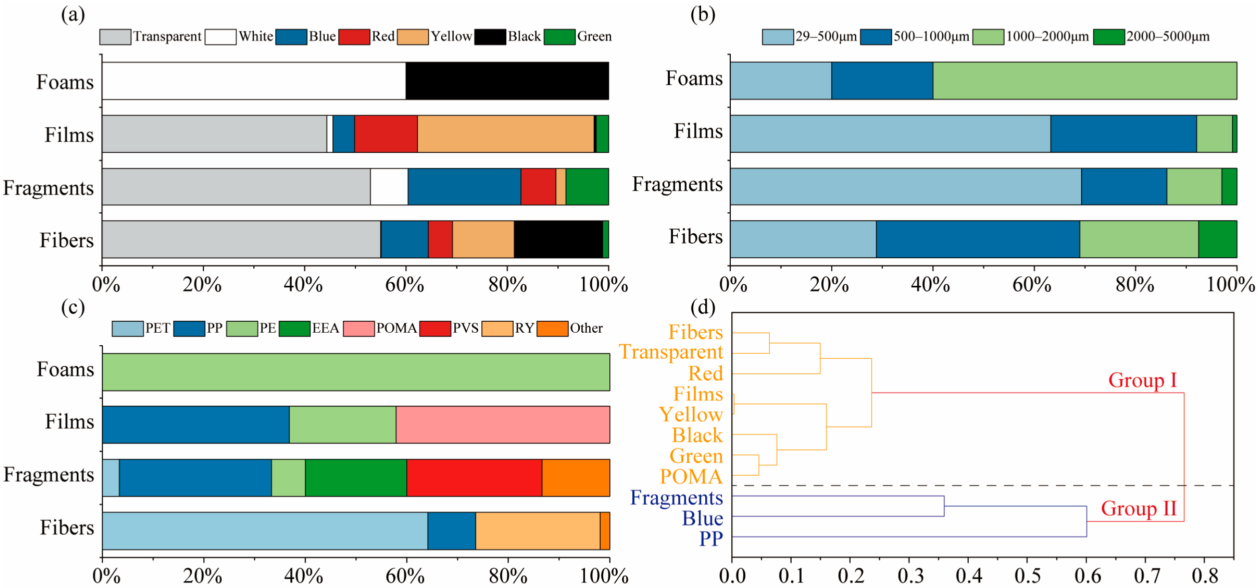

Figure 4. Distribution of colors (**a**), sizes (**b**), and polymers (**c**) in different MP shapes. Cluster analysis of the main characteristics of MPs (**d**).

3.4. Relevance of MPs to Environmental Factors

SOC content and its components (fPOC, oPOC, MAOC, and DOC) were significantly higher in L than in the other five sampling areas ($p < 0.05$, Table S2, Figure S3j–n). For soil physicochemical properties, the TN content and EC in L were significantly higher, and the BD was significantly lower compared to the other five sampling areas ($p < 0.05$, Table S3, Figure S3b,e,g). Moreover, pH was significantly higher in RU and RD than in CU, CM, CD, and L ($p < 0.05$, Figure S3c).

Spearman correlation analysis revealed a significantly positive correlation between the MP abundance and oPOC content ($p < 0.05$, Figure 5a). The two principal components of PCA explain 90.5% of the influence of soil physicochemical properties on MP abundance (Figure 5b). Furthermore, positive PC1 was found to be correlated with TN and NH_4^+-N, while negative PC1 was correlated with pH and BD.

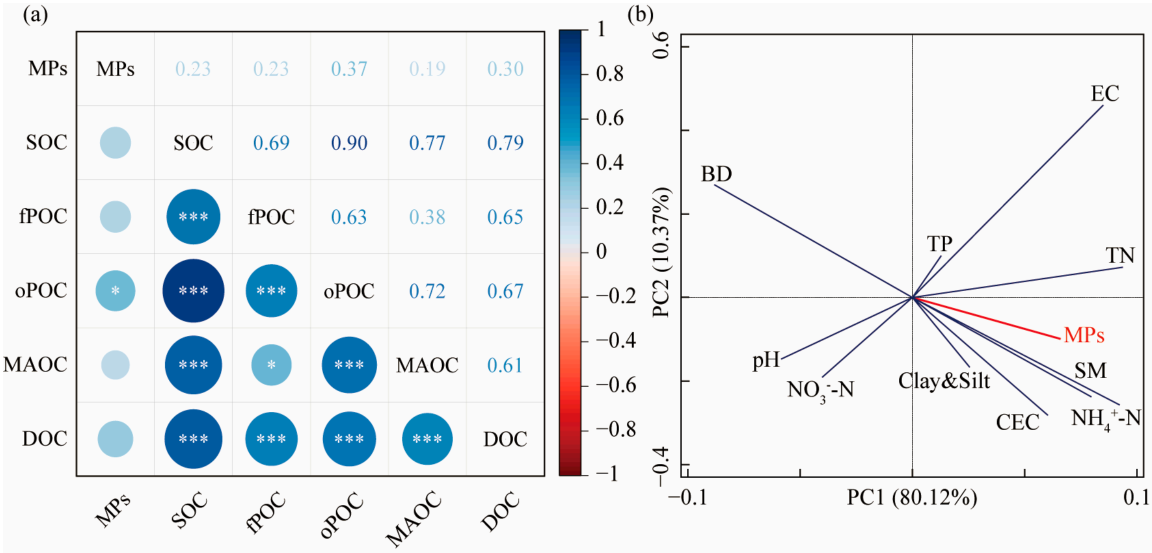

Figure 5. Relationship between MP abundance and environmental factors. (**a**) Spearman correlation analysis of MPs with soil organic carbon and its components (* $p < 0.05$, *** $p < 0.001$); (**b**) PCA of MP abundance and soil physicochemical properties.

4. Discussion

4.1. Abundance and Characteristics of MPs

The average abundance of MPs in the inland wetland was 1203 ± 799 items/kg. MP abundance might be closely related to human activities. Population density and economic development level are important factors in determining the level of MP pollution [44,45]. For example, the Tibetan Plateau is a region characterized by underdevelopment, with a weak economic base, sparse population distribution, and a very low level of industrialization. As a result, the detected levels of MP abundance are extremely low [46]. The abundance of MPs in the sediments of the Brahmaputra and Koshi Rivers were 53 ± 21 and 58 ± 27 items/kg, respectively [47,48]. The higher abundance of MPs in the inland wetland compared to the Tibetan Plateau is expected, given the higher population density and industrialization levels in Jining City. However, MP pollution levels were extremely high in wetlands in Sichuan Province, where the population density was lower than in Shandong Province. The abundance of MPs in the Qionghai wetland reached 5.55 ± 4.92 items/g, a level considerably greater than what was observed in the inland wetland as referenced in the study [49]. The results may be due to the choice of sampling location, extraction method of MPs, sensitivity of the instrument, and local economic structure [50]. In addition, land use patterns also affect MP abundance. Agricultural soils have higher levels of MP pollution compared to wetland soils [51]. The abundance of MPs in agricultural soils in Xiangtan, China, was 4377 items/kg, with a maximum of 12,292 items/kg [37]. The average abundance of MPs in agricultural soils in Chengdu was 6874 ± 2628 items/kg, which was significantly higher than those in inland wetlands [52]. In conclusion, compared with other regions in the world, the MP pollution in the inland wetland is at a medium level; its ecological risk should not be ignored, and the attention to MP pollution in this area should be strengthened.

It was found that the most prevalent colors of MPs were transparent (53.2%) and yellow (15.1%), partly due to the sources of MPs and partly because MPs gradually fade to transparent after long-term photooxidation and photodegradation in the natural environment [53]. Fibers are prevalent in the river wetland, constructed wetland, and lake wetland and are the most common shapes (51.2%) in wetland soils, similar to wetlands such as the Ergene River [54], Yitong River [55], and Gulf of Thailand [56]. Fibers are more likely to be retained by wetland plants and accumulate in wetland soils because they have a unique linear structure that allows them to become entangled with soil particles, thus promoting the formation of soil aggregates compared to films and fragments [57]. In addition, the smaller the size, the higher the abundance of MPs, similar to previous studies [58,59]. This is because MPs are gradually fragmented into smaller MPs after ultraviolet aging, mechanical fragmentation, and microbial degradation in the environment. Smaller MPs are easily colonized by microorganisms, leading to the formation of biofilms, which increases the density of floating MPs and makes them easier to deposit [60]. Moreover, smaller-sized MPs have stronger aggregation and higher deposition rates and are more likely to migrate from the water column to the soil, whereas larger-sized MPs are subjected to stronger buoyancy forces and are more likely to migrate with the water flow [61].

4.2. Distribution of MPs in Inland Wetland Ecosystems

MP abundance in the river-constructed-lake wetlands was as follows: lake wetland (2613 ± 1092 items/kg), river wetland (1033 ± 267 items/kg), and constructed wetland (847 ± 263 items/kg) (Figure 1b). Field investigation showed that plastic pollution was serious in the river, and plastic wastes such as domestic rubbish, residual mulch, fertilizer, and pesticide packages could be found everywhere along the bank, as well as domestic sewage and industrial wastewater from the nearby towns were finally discharged into the river after treatment (Figure S4a–c). However, MP pollution in the river wetland is not the most serious in the inland wetland ecosystem, which is related to the migration of MPs. The river is flowing faster, and the high flow rate led to the migration of MPs from the source to the sink, which in turn led to the reduction of MP abundance in the river [30].

It has been shown that MPs can be significantly removed by plant interception, animal feeding, substrate adsorption, and microbial degradation in constructed wetlands [28]. However, the constructed wetland in this study could not significantly remove MPs, which may be due to a number of factors. For example, the shapes, sizes, and polymers of MPs, soil properties and biofilm formation can affect the deposition of MPs [29]. The field investigation showed that green planting, tourists visit, and facility construction in the constructed wetland would introduce new plastic pollution, which can lead to the weakening of MP removal in the constructed wetland (Figure S4d,e). In addition, the wastewater treatment process significantly impacts the efficiency of MP removal [27].

The abundance of MPs in the lake wetland was significantly higher compared to the river wetland and constructed wetland, which was related to the migration and accumulation of MPs in the inland wetland ecosystem ($p < 0.05$, Figure 1b). In many studies, lakes have been recognized as a major sink for MPs in freshwater systems [62–64]. The inland wetland ecosystem in this study is a unique hydrological system where the lake is the sink of many surrounding rivers because the drainage basin does not have access to the sea. Macroplastics and MPs in the rivers migrate horizontally along the surface runoff into the lake and are gradually fragmented into smaller MP particles during the migration process [65]. Due to the lack of outlet channels, the lake forms a closed environment, leading to long-term storage of MPs and ultimately to severe plastic pollution [66]. This cumulative effect may lead to the degradation of lake wetland ecosystems, which in turn affects the ecological service functions of lakes, and appropriate management measures should be taken to address the potential ecological risks.

4.3. Sources of MPs in Inland Wetland Ecosystems

Fibers are the most common shape in soils of the inland wetland ecosystem. The lake is a famous freshwater fishery base in China, with rich fish resources and diverse fishing activities. The survey found that a large number of fishponds existed in the area and discarded fishing nets and gears were found near some of the sampling sites. The fibers mainly consisted of three polymers: PET, PP, and RY. PET and PP might come from discarded fishing nets, lines, floats, nets, and culture pens, while RY is more likely to come from discarded garments, blankets, and curtains [67]. Meanwhile, transparent (55.0%) was the main color of fibers. This fact further proves that aquaculture is the most important source of fibers because most of the MPs released by textiles are colored fibers [36]. In addition, fibers released from clothing, household textiles, feminine hygiene products and disposable medical surgical masks are also sources of MPs in the inland wetlands [68,69].

The main components of the fragments are PP and PVS, which may come from the plastic packaging of food, beverages, pesticides, and fertilizers [70]. Higher concentrations of fragments were detected in RU, RD, and CU compared to CM, CD, and L. This is due to the lack of systematic management of the pollution in the river, which has resulted in a very low rate of plastic recycling. Domestic waste and agricultural waste accumulate over time, releasing MPs. In contrast, there is no significant amount of plastic waste around the constructed wetland and lake wetland. The field survey found that the most common plastic product in the constructed wetland was disposable black PP seedling pots, but no black fragments were found in the soil. Plastics are difficult to degrade in the environment; the seedling pots in the constructed wetland have been in existence for a short time and failed to age, break up to form MPs, and be released into the environment. However, the potential ecological risks cannot be ignored [71].

The films in this study mainly consisted of PP, PE, and POMA, and the distribution of films varied significantly among the sampling sites. PP and PE are frequently utilized as materials for agricultural mulching [50]. Agricultural fields around RU and RD are planted with crops such as maize, wheat, and vegetables and covered with mulch to improve water and heat use efficiency and crop yields [72]. These mulches undergo ultraviolet irradiation and mechanical abrasion, releasing large amounts of MPs into the environment [73]. Furthermore, a new polymer type, POMA, which can be used for wastewater treatment filter membrane production and modification of waxy crude, has been detected in the constructed wetland and lake wetland [74,75]. Possible sources include sewage filtration systems, asphalt roads, fuel, and lubricants for construction machinery in the constructed wetland, and pleasure boats in the lake.

Human activities such as agricultural production, fishery farming, rubbish dumping, and sewage discharge are concentrated in the river basin. However, associated MP pollution also occurs in constructed wetland and lake wetland soils, which may result from the transport of surface runoff [76]. In addition, atmospheric deposition could contribute to the presence of MPs in wetlands, and even in some areas, the amount of MPs entering wetlands through atmospheric deposition has far exceeded the introduction of wastewater discharges [21]. In particular, MPs lighter in mass and smaller in size are more readily transported with water and air currents and are captured and stored by the abundant plants in wetlands [77].

4.4. Influencing Factors and Management of MP Pollution

MP abundance correlated positively with oPOC, TN, and NH_4^+-N content, so it can be inferred that agricultural and fishery processes might be an important source of MPs in the study area [59,78]. MP abundance was negatively correlated with soil pH, which is similar to numerous prior investigations [50,79]. pH significantly affects the abundance of MPs in wetland soils. Lower pH promotes mutual adsorption of MP particles by reducing the negative charge on the surface of MPs, which increases the migration rate of MPs [80]. MP pollution is greatly influenced by environmental factors, and it is important to understand the interactions between MPs and environmental factors. Therefore, further studies are needed to demonstrate the mechanism of interaction between MPs and environmental factors and to reveal the effects of environmental factors on MP transport, aggregation, deposition, fragmentation, and degradation.

The study revealed the abundance, characteristics, sources and influencing factors of MPs in the inland wetland ecosystem, further demonstrating that MPs management is a major challenge in the current context. MPs management consists of four main aspects: source reduction, recycling, ecological restoration, and awareness raising [81]. Frequent aquaculture and agricultural activities in the inland wetland are the main sources of MPs. Optimizing the structure of fisheries and agriculture and strengthening their management are important measures to reduce MP pollution [66]. The use of fishing gear and mulch made from environmentally friendly materials, as well as improved packaging of fish and agricultural products, are among the ways to reduce MP pollution [82]. Plastic waste visible in the river wetland is a potential source of MPs (Figure S4a–c). Strengthening domestic waste management in rural areas and establishing a better waste recycling system would effectively reduce MP pollution [83]. For MPs that have entered the wetland environment, bioremediation is considered an economical and environmentally friendly method [84]. In addition, raising the awareness of governments, enterprises, and residents about the ecological risks of MP pollution is essential to control the further spread of MP pollution. Finally, we recommend standardizing the methodologies of MP extraction and identification, unifying the statistical units of MP abundance, and establishing a standard system for monitoring MP pollution to facilitate the assessment of MP pollution [85].

5. Conclusions

The study revealed that MPs were widely distributed in the soils of all sampled inland wetlands, with an average abundance of 1203 ± 799 items/kg. In comparison to other regions worldwide, the level of MP pollution in the area was moderate. Notably, the constructed wetland did not significantly remove MPs in this study. The lake may be one of the sinks for MP pollution in the inland wetland ecosystem because of its unique and closed environment. The characteristics analysis of MPs suggested that aquaculture, agricultural cultivation, sewage discharge, and domestic rubbish are the main sources of MPs. Therefore, we recommend that the government and residents should pay more attention to the management of fishery activities, agricultural activities, and domestic rubbish and establish a more comprehensive rubbish recycling and treatment system. MP pollution and environmental factors interact with each other, but the mechanism of their interaction needs further research. The study provides an important understanding of the distribution of MPs in inland wetland ecosystems and is a basis for future risk assessment and ecological protection.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w17020231/s1, Table S1: Results of μ-FTIR identification of MPs polymer types; Table S2: Soil carbon content in different wetland soils. Values are means ± standard error (SE); Table S3: Physicochemical properties of different wetland soils. Values are means ± standard error (SE); Figure S1: Sampling sites in the inland wetlands of Nansi Lake, Jining City, Shandong Province. The red point represents a sampling site. RU—river upstream; RD—river downstream; CU—constructed wetland inlet; CM—constructed wetland midstream; CD—constructed wetland outlet; L—lake wetland; Figure S2: Pictures of microplastics taken by stereomicroscopy. Fibers (a–e), films (f) and fragments (g–i); Figure S3: Results of soil physicochemical properties in different wetlands. Different superscript lowercase letters indicate significant differences ($p < 0.05$); Figure S4: Potential plastic pollution in inland wetland ecosystems. The river wetland (a–c), constructed wetland (d,e), and lake wetland (f).

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