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Analysis of Occurrence Characteristics and Spatial Distribution of Microplastics in Water and Sediments of Dongting Lake

Liqun Xu, Tianxiao Han, Wei Yu

School of Geography & Environment, Baoji University of Arts and Sciences, Baoji, China
Email: xuliqun6515@163.com

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Abstract

To explore the current occurrence status and spatial differentiation pattern of microplastics in the water and sediments of Dongting Lake, and provide scientific support for the prevention and control of microplastic pollution in the lake area, this paper adopts the integrated analysis approach of multi-source literature. We systematically collected and screened 10 pieces of in-situ measurement literature on microplastics in Dongting Lake, extracted relevant data of microplastics in surface water and surface sediments from the whole lake as well as the west, south and east lake regions. After standardized processing including unit unification, classification caliber alignment and outlier elimination, we analyzed the occurrence characteristics of microplastics from multiple dimensions: abundance, morphology, particle size, polymer type and color, and revealed the spatial distribution pattern and main influencing factors. The results showed that the detection rate of microplastics in both water and sediments of Dongting Lake was 100%. The abundance of microplastics in surface water ranged from 900 to 2500 items/m^3, with an average of 1700 items/m^3; the abundance of microplastics in sediments ranged from 20 to 1200 items/kg (dry weight), with an average of 610 items/kg (dry weight). Fibers were the dominant morphology of microplastics across the whole lake, and particles smaller than 0.5 mm accounted for the highest proportion. The main polymer types were PET, PE, PP and PA, and the dominant colors were transparent and blue. Regulated by settling dynamics and polymer density, there were obvious medium differences in the occurrence characteristics of microplastics between water and sediments. Sediments had a significant enrichment effect on small-sized and granular microplastics. Spatially, the overall microplastic pollution presented a gradient pattern of West Dongting Lake > South Dongting Lake > East Dongting Lake. The estuaries of inflowing rivers were high-value pollution areas, while the Chenglingji outlet and the East Dongting

Lake Nature Reserve were low-value areas. The spatial variation trends of microplastics in water and sediments were basically consistent. Land-based runoff input, human activities in the basin, together with the unique hydrodynamic sorting and seasonal hydrological processes of the river-connected lake, jointly dominated the spatial differentiation of microplastics in Dongting Lake. The differences in microplastic components among different lake regions can indirectly indicate potential pollution sources such as agriculture, aquaculture and inland shipping. This study makes up for the deficiency of scattered data in existing single-site studies, and can provide basic reference for zonal management of microplastics and drinking water source protection in Dongting Lake.

Keywords

Dongting Lake, Microplastics, Spatial Distribution, Occurrence Characteristics

1. Introduction

The widespread use of plastics has led to the formation of microplastics (particle size < 5 mm) through environmental weathering after abandonment, which have been listed as a new type of global persistent environmental pollutant [1]. Since Thompson *et al*. formally proposed the concept of microplastics in 2004 [2], their environmental behavior and ecological risks have become a research hotspot in the field of environmental science. Microplastics are divided into primary and secondary types according to their sources, among which secondary microplastics account for more than 80% of the total and are the core source of pollution in freshwater ecosystems [3]. With large specific surface area, strong mobility and long degradation cycle, microplastics can not only cause toxic effects such as oxidative stress and reproductive damage to aquatic organisms and disrupt the structural stability of aquatic ecosystems [4] [5], but also adsorb heavy metals and persistent organic pollutants to form combined pollution. They can enter the human body through bioaccumulation in the food chain and drinking water intake, and their long-term health risks have attracted key attention from the global public health field [6] [7].

Microplastic research originated from marine ecosystems. With the deepening of research, the problem of microplastic pollution in freshwater lakes, as an important sink of land-based pollutants, has become increasingly prominent [8]. The systematic investigation of the Great Lakes in North America in 2013 confirmed the universality of microplastic pollution in large freshwater lakes, and promoted the expansion of research from basic characteristic investigation to spatial distribution, migration and transformation, pollution source tracing and other directions [3] [9]. Research on microplastics in freshwater lakes in China began with the systematic investigation of Taihu Lake in 2015 [10]. Subsequent studies on

lakes such as Poyang Lake, Chaohu Lake and Honghu Lake in the middle and lower reaches of the Yangtze River showed that the microplastic pollution level of lakes was significantly correlated with the intensity of surrounding human activities, and hydrodynamic conditions and hydrological cycles were the key factors regulating the migration and distribution of microplastics in river-connected lakes [11] [12]. However, current studies on river-connected lakes are mostly single-time and single-lake-region investigations, lacking systematic integrated analysis at the whole-lake scale and across multiple media. The data comparability among different studies is poor, making it difficult to form a unified understanding of pollution characteristics [13].

Dongting Lake is the second largest freshwater lake in China and the only large river-connected lake in the middle reaches of the Yangtze River. It receives water from the Xiang, Zi, Yuan and Li rivers as well as the three outlets of the Yangtze River [14]. It serves as a flood regulation hub of the basin, an internationally important wetland and a regional core drinking water source, and its water environment quality is directly related to regional ecological security and sustainable development [15]. As a typical river-connected lake, Dongting Lake has the seasonal hydrological feature of "forming a lake in flood season and exposing shoals in dry season", and the complex river-lake exchange process directly regulates the migration, diffusion and settling of pollutants [16]. At present, most studies on microplastics in Dongting Lake are local investigations of single lake region and single medium, with great differences in sampling and detection methods. The pollution characteristics and spatial distribution pattern at the whole-lake scale are still unclear, which can hardly support basin pollution prevention and control [17].

Based on this, this study systematically retrieved and screened 10 in-situ measurement literatures on microplastics in Dongting Lake. After standardized processing, we systematically analyzed the occurrence characteristics of microplastics in water and sediments, including abundance, morphology, particle size and polymer type, and revealed the spatial distribution pattern and differentiation law of the whole lake. The results can make up for the shortcomings of scattered existing studies and poor data comparability, construct a unified basic dataset of microplastic pollution across the whole lake, identify high-risk areas and core sources, and provide scientific basis for overall prevention and control of microplastic pollution and drinking water source protection in Dongting Lake [18].

2. Data and Methods

2.1. Study Area

Dongting Lake (28˚30' - 30˚20'N, 110˚40' - 113˚10'E) is located on the south bank of the Jingjiang River in the middle reaches of the Yangtze River (in **Figure 1**). It is the second largest freshwater lake in China and the only large river-connected lake in the middle reaches of the Yangtze River, serving as the core flood regulation hub, internationally important wetland and ecological security barrier of the

Yangtze River Basin. According to natural hydrological units and basin confluence pattern, the lake area can be divided into three core lake regions: West Dongting Lake, South Dongting Lake and East Dongting Lake, forming a one-way confluence pattern of "receiving inflows from the west and discharging into the Yangtze River to the east". West Dongting Lake is the first receiving area of upstream inflows, receiving water from the Yuan and Li rivers as well as the Songzi, Taiping and Ouchi outlets of the Yangtze River. South Dongting Lake is the hydrological transition zone between the west and east lake regions, receiving tail water from the Xiang and Zi rivers and runoff discharged from West Dongting Lake. East Dongting Lake is the final collection area of all inflows from the whole lake, which flows into the main stream of the Yangtze River through Chenglingji in the northeast after regulation. The annual average inflow runoff of the lake area is about 301.8 billion m^3 [14].

Regulated by basin precipitation and Yangtze River inflow, the water level fluctuates significantly within the year, with the seasonal hydrological characteristic of "forming a lake in flood season and exposing shoals in dry season". The complex hydrodynamic conditions and river-lake exchange process directly determine the migration, diffusion and settling rules of microplastics in the lake area [19]. Meanwhile, the Dongting Lake Basin is an important commodity grain, cotton, oil and aquaculture base in China, surrounding cities such as Yueyang, Changde and Yiyang, with intensive human activities including agricultural planting, aquaculture, inland shipping, urban industry and domestic life [20]. Residues of agricultural plastic film, loss of aquaculture facilities, urban sewage discharge and shipping pollution are the main input pathways of microplastic pollution in the lake area, and its pollution characteristics are highly coupled with regional human activities and hydrological conditions [21].

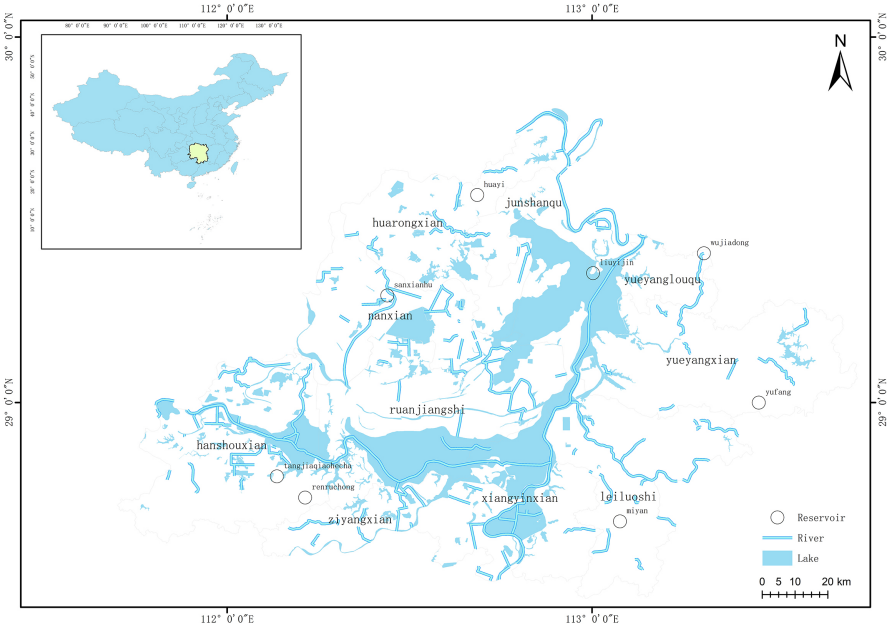


Figure 1. Overview of the Dongting Lake water system.

2.2. Data Sources and Literature Screening

All data in this study are derived from published academic papers related to microplastic pollution in Dongting Lake. CNKI, Web of Science and ScienceDirect were used as retrieval databases, with the retrieval time spanning from database establishment to December 31, 2025. The Chinese search string was set as ("洞庭湖" AND "微塑料" AND ("淡水" OR "沉积物" OR "地表水")), and the English search string was ("Dongting Lake" AND ("microplastic" OR "micro plastic") AND ("surface water" OR "sediment" OR "freshwater")). Backward snowball searching was also conducted on the reference lists of initially eligible studies to cover all relevant public reports as much as possible. Through four steps: literature retrieval, standardized screening, index extraction and standardized correction, a standardized dataset of microplastic pollution in Dongting Lake was constructed [22].

2.2.1. Literature Retrieval and Screening

A total of 87 preliminary records were identified through database retrieval and supplementary searching. After removing duplicates (n = 31), title and abstract screening (n = 35 excluded for irrelevant research objects or review articles), and full-text assessment (n = 11 excluded for non-natural lake water bodies, lack of raw data, or inconsistent detection methods), 10 eligible in-situ measurement studies were finally included [1] [6] [9] [10] [23]-[30], containing 250 valid sampling points in total. All sampling points represent independent field locations in the natural lake body, with no repeated temporal observations at the same site.

The inclusion criteria for data screening included: 1) The literature has clear sampling time and sampling locations, and sampling points are surface water or surface sediments in the natural lake body of Dongting Lake, excluding artificial controlled water bodies such as ditches, ponds and aquaculture ponds; 2) The sampling depth of surface water is 0 - 50 cm, and the sampling depth of surface sediments is 0 - 10 cm; 3) Sample pretreatment adopts hydrogen peroxide (H_2O_2) or Fenton reagent for organic matter digestion, combined with density flotation using salt solutions such as NaCl and $ZnCl_2$ to separate microplastics; 4) Microplastic identification must combine microscopic morphological observation and polymer spectral verification, using Fourier Transform Infrared Spectroscopy (FTIR), micro-Fourier Transform Infrared Spectroscopy (μFTIR) or micro-Raman spectroscopy; 5) The literature provides at least one type of occurrence characteristic data (abundance, morphology, particle size or polymer type) of microplastics, with convertible data units and complete extractable information.

2.2.2. Data Extraction and Standardized Processing

Index extraction and data standardization were carried out on the screened valid literatures. The extracted contents included sampling point information, sampling time, hydrological conditions, as well as original data of microplastics in water and sediments: abundance, morphological composition, particle size distribution, polymer type, color proportion, etc.

To eliminate systematic deviation caused by differences in classification calibers, measurement units and analytical methods among different studies, data standardization was carried out as follows: 1) Unit unification of abundance. The abundance of microplastics in water was uniformly converted to items/m^3, and the abundance in sediments was uniformly converted to items/kg (dry weight) [22] [31]. For data recorded in items/100 g, direct unit conversion was performed by mass scaling. For area-based abundance data (items/km^2) from trawl sampling, conversion to volume-based abundance was calculated based on the trawl depth (0.5 m, consistent with the 0 - 50 cm surface water sampling standard) and net mouth area parameters provided in original studies, and conversion records were retained. 2) Unification of classification calibers. Morphologies were merged into four categories: fibers, granules, fragments and films. Particle sizes were uniformly divided into four grades: <0.5 mm, 0.5 - 1 mm, 1 - 2 mm and >2 mm [3] [22]. For studies with different lower particle-size cutoffs (ranging from 20 μm to 100 μm), we unified the statistical caliber to >20 μm by referring to the minimum detection limit of included studies, and noted that differences in lower size limits may lead to slight underestimation of small-particle proportion in studies with higher detection thresholds [31]. Polymers were uniformly named with standard abbreviations, and subcategories in literatures were merged into corresponding major categories according to physical properties. For density separation methods, both NaCl (1.2 g/cm^3) and $ZnCl_2$ (1.5 - 1.6 g/cm^3) were accepted; we acknowledged that $ZnCl_2$ solution can recover more high-density polymers, while NaCl may slightly underestimate high-density polymer abundance. This methodological difference was controlled by only comparing relative proportions of polymer types rather than absolute abundance across studies [32] [33]. 3) Outlier elimination. The 3-sigma criterion was used to identify and eliminate extreme outliers in the original abundance dataset, so as to reduce the interference of abnormal samples caused by sampling or detection errors on statistical results [34] [35].

2.3. Data Analysis Methods

Excel 2021 was used to sort out and conduct basic descriptive statistics on the standardized multi-source literature data. Whole-lake and regional mean values of microplastic abundance were calculated via sample-size weighting, with the number of valid sampling points in each lake region as the weighting denominator, to ensure that aggregated whole-lake abundance results reflect the actual spatial coverage of sampling sites.

For morphological, particle size and polymer composition proportions, whole-lake overall values and zonal values were counted independently from different subsets of the included literature. Whole-lake composition data were derived from studies that carried out full-lake surveys and reported overall lake-wide proportions, while zonal composition data were only extracted from sampling points with clearly marked lake region locations. The two sets of data do not fully overlap in literature sources and sampling coverage, so the whole-lake proportions cannot

be directly derived by weighted aggregation of the three lake regions.

A total of 7 outlier abundance samples (3 in water, 4 in sediments) were excluded by the 3-sigma criterion, accounting for 2.8% of all valid samples. Sensitivity analysis showed that retaining these outlier samples did not change the spatial ranking of microplastic abundance (West Dongting Lake > South Dongting Lake > East Dongting Lake), and only slightly increased the whole-lake mean value by 4.2% - 5.7%, indicating that the outlier removal did not eliminate genuine pollution hotspots but only reduced extreme measurement noise.

Origin 2023 was used to draw graphs of morphological composition, particle size distribution, polymer type and color proportion of microplastics in water and sediments, to intuitively compare the differences in composition structure among the whole lake and each lake region. On this basis, zonal comparative analysis was carried out for the three major lake regions, combined with hydrological conditions and human activity characteristics of the lake areas, to explore the spatial differentiation law of microplastic occurrence characteristics and its possible influencing factors.

3. Occurrence Characteristics of Microplastics in Dongting Lake

3.1. Abundance Characteristics

Based on the standardized integration results of 10 literatures, the detection rate of microplastics in both water and sediments across Dongting Lake was 100%, indicating that microplastic pollution is widespread in the whole lake, which is consistent with the pollution status of most freshwater lakes in the middle and lower reaches of the Yangtze River in China [36].

For surface water, microplastic abundance ranged from 900 to 2500 items/m^3, with a sample-weighted mean of 1700 items/m^3 and a standard deviation of ±420 items/m^3. As the main medium for microplastic migration and transport, surface water is sensitive to fresh pollution input and shows high spatial dispersion regulated by hydrological processes such as inflow runoff and wind-wave disturbance. For surface sediments, microplastic abundance ranged from 20 to 1200 items/kg (dry weight), with a sample-weighted mean of 610 items/kg (dry weight) and a standard deviation of ±310 items/kg; as the long-term "sink" of microplastics in freshwater ecosystems, sediments are less affected by short-term disturbances and have a stronger cumulative retention effect, serving as an important indicator reflecting the long-term pollution level of lakes [37]. It should be noted that abundance units differ between water (volume-based) and sediments (mass-based), so direct comparison of absolute magnitude between the two media is not applicable.

As a typical river-connected lake in the middle reaches of the Yangtze River, Dongting Lake has the seasonal hydrological feature of "forming a lake in flood season and exposing shoals in dry season", which drives the dynamic source-sink transformation of microplastics between water and sediments, and constitutes a long-term internal source of microplastic pollution in the lake area [38].

Compared with similar freshwater lakes in the middle and lower reaches of the Yangtze River Basin, the abundance of microplastics in surface water of Dongting Lake is at a medium to high level, slightly lower than that of Poyang Lake (mean 2300 items/m^3) [39], and significantly higher than that of the closed lake Chaohu (mean 930 items/m^3) [40]. The abundance of microplastics in sediments is in the same order of magnitude as Taihu Lake (mean 580 items/kg) [10] and Hongze Lake (mean 630 items/kg) [41], which conforms to the overall distribution characteristics of microplastic pollution in river-connected lakes of the Yangtze River Basin, and also verifies the reliability of the standardized dataset in this paper.

3.2. Morphological Composition Characteristics

Fibers were the absolutely dominant morphology of microplastics across the whole lake, accounting for more than 50% in both surface water and sediments, followed by granules and fragments, with films accounting for the lowest proportion.

Specifically, in surface sediments of the whole lake, fibers accounted for 53.29%, granules 26.32%, fragments 17.54%, and films 2.85%; in surface water, fibers accounted for 64.20%, fragments 25.70%, granules 4.30%, and films 5.80%. It should be noted that the whole-lake sediment composition statistics are based on full-lake survey data, which are not completely consistent with the data sources of zonal statistics, so there are differences in numerical ranges.

The proportion of morphologies differed significantly between media: the proportion of fibrous microplastics in surface water was significantly higher than that in sediments; while the proportion of granular microplastics in sediments was much higher than that in surface water. This difference is controlled by settling dynamics: fibrous microplastics have a large length-diameter ratio, long suspension time and long migration distance in water, hence a higher proportion in water; granular microplastics have higher density and faster settling velocity, so they are more likely to be enriched in sediments [42].

3.3. Particle Size Distribution Characteristics

Microplastics in Dongting Lake are dominated by small-sized particles smaller than 0.5 mm. The proportion of small-sized microplastics reached 69.63% in sediments and 46.30% in surface water across the whole lake.

In detail, in sediments, particles <0.5 mm accounted for 69.63%, 0.5 - 1.0 mm accounted for 18.07%, and particles >2.0 mm accounted for only 3.78% in total; in surface water, particles <0.5 mm accounted for 46.30%, 0.5 - 1.0 mm accounted for 28.70%, and particles >2.0 mm accounted for 9.80% in total.

The enrichment effect of small-sized microplastics in sediments is very prominent, while the proportion of large-sized microplastics in surface water is relatively higher. On the one hand, small-sized microplastics have large specific surface area, which are easy to adsorb and agglomerate with suspended particles and

algal flocs, increasing the equivalent density and accelerating the settling process [43]. On the other hand, small-sized microplastics can enter the deep layer of sediments with pore water and are difficult to resuspend, thus continuously accumulating in the bottom sediment [44]. The high proportion of small-sized particles also reflects the reality of long-term aging and fragmentation of plastic waste in the lake environment. The morphological composition and particle size distribution of microplastics in surface water and sediments are intuitively presented in **Figure 2**.

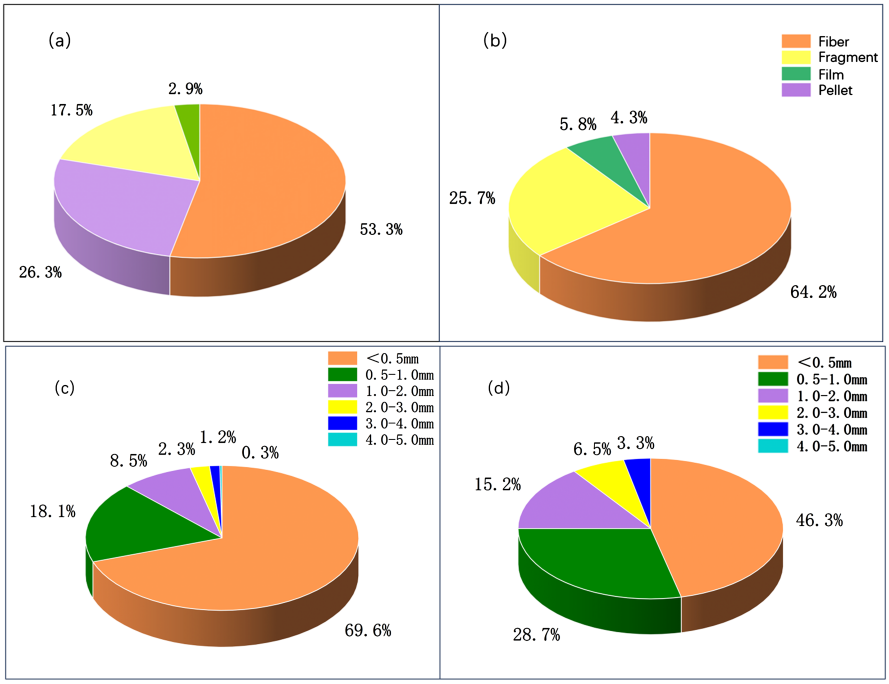


Figure 2. Proportion of morphology and particle size of microplastics in water and sediments of Dongting Lake (a) Morphological proportion of microplastics in sediments; (b) Morphological proportion of microplastics in water; (c) Particle size proportion of microplastics in sediments; (d) Particle size proportion of microplastics in water.

3.4. Polymer Type Characteristics

The dominant polymer types in surface water and sediments of Dongting Lake are basically consistent, mainly including polyethylene terephthalate (PET), polyethylene (PE), polypropylene (PP) and polyamide (PA). The total proportion of these four polymers reaches 72.5% in surface water and 77.28% in sediments.

Specifically, in sediments, PET accounted for 29.55%, PA 19.32%, PE 15.91%, and PP 12.50%; in surface water, PET accounted for 28.50%, PE 18.70%, PP 17.90%, and PA 7.40%. Different polymers show density-dependent medium differentiation: high-density polymers are more likely to be enriched in sediments, while low-density polymers tend to suspend and migrate in water [45] [46]. The overall polymer proportion of microplastics in the two media is visualized in **Figure 3**.

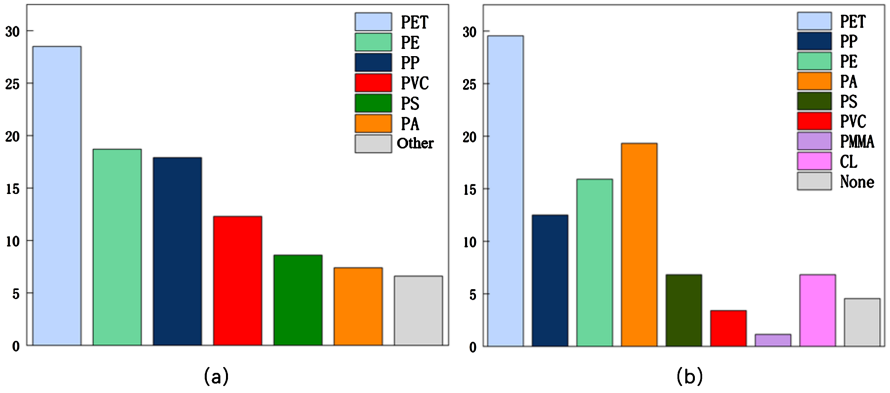


Figure 3. Overall polymer proportion of microplastics in water and sediments of Dongting Lake.

In terms of color characteristics, transparent and blue are the dominant colors of microplastics in Dongting Lake. The total proportion of the two reaches 61.1% in surface water, and accounts for nearly 50% (49.71%) in sediments. Among them, in sediments, transparent accounted for 31.17%, blue 18.54%, white 16.83%, and black 13.24%; in surface water, transparent accounted for 39.60%, blue 21.50%, black 18.30%, and white 11.20%. Transparent microplastics mostly indicate the input of daily necessities; blue microplastics can be used as an auxiliary indicator for aquaculture sources. The color composition of microplastics in water and sediments is shown in **Figure 4**.

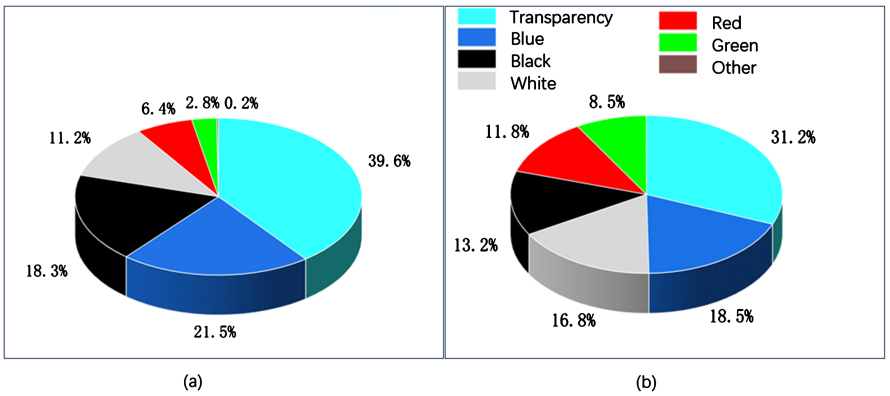


Figure 4. Overall color proportion of microplastics in water and sediments of Dongting Lake.

4. Spatial Distribution Characteristics of Microplastics in Dongting Lake

4.1. Spatial Gradient Differentiation of Abundance

The abundance of microplastics in the three major lake regions of Dongting Lake presents a significant spatial gradient differentiation feature of West Dongting Lake > South Dongting Lake > East Dongting Lake, and the distribution patterns of surface water and sediments are highly consistent, which fully matches the confluence pattern of "receiving inflows from four rivers and three outlets in the west,

discharging into the main Yangtze River in the east" [47].

As the first receiving area of upstream inflows, West Dongting Lake receives all inflows from the three outlets of the Yangtze River and the Yuan and Li rivers, with the strongest land-based input intensity. The average abundance of microplastics in surface water reaches 2100 items/m^3, and the average abundance in sediments reaches 890 items/kg, both the highest in the whole lake.

As the midstream transition zone, South Dongting Lake receives tail water from the Xiang and Zi rivers and runoff discharged from West Dongting Lake, with medium pollution load. The average abundance of surface water is 1800 items/m^3, and the average abundance of sediments is 570 items/kg.

As the only outlet channel of the whole lake, microplastics in East Dongting Lake flow into the Yangtze River through Chenglingji along with runoff, with significant emigration effect. In addition, due to the strict management of the national nature reserve, the abundance is the lowest in the whole lake. The average abundance of surface water is 1200 items/m^3, and the average abundance of sediments is 370 items/kg. Detailed statistical parameters of microplastic occurrence in different lake regions are summarized in Table 1.

Table 1. Statistics of microplastic occurrence in water and sediments of different lake regions in Dongting Lake.

Lake Region	Medium	Number of Valid Samples	Mean	Abundance Range	Standard Deviation
West Dongting Lake	Surface water	42	2100 items/m^3	1220 - 2500 items/m^3	±460 items/m^3
West Dongting Lake	Surface sediment	38	890 items/kg	320 - 1200 items/kg	±340 items/kg
South Dongting Lake	Surface water	36	1800 items/m^3	1040 - 2340 items/m^3	±410 items/m^3
South Dongting Lake	Surface sediment	34	570 items/kg	200 - 960 items/kg	±280 items/kg
East Dongting Lake	Surface water	48	1200 items/m^3	900 - 1720 items/m^3	±320 items/m^3
East Dongting Lake	Surface sediment	52	370 items/kg	20 - 690 items/kg	±210 items/kg
Whole Lake Summary	Surface water	126	1700 items/m^3	900 - 2500 items/m^3	±420 items/m^3
Whole Lake Summary	Surface sediment	124	610 items/kg	20 - 1200 items/kg	±310 items/kg

Combined with basin confluence characteristics and point survey results of existing literatures, Dongting Lake can be divided into three types of pollution areas: a) High-value areas are mainly the estuaries of the three Yangtze outlets in West Dongting Lake, and the estuaries of Xiang River and Zi River in South Dongting Lake, which are the main input ends of land-based pollutants, with microplastic abundance at a high level in the whole lake; b) Medium-value areas are concentrated in the core lake areas of West Dongting Lake and South Dongting Lake, with medium pollution load; c) Low-value areas are mainly the East Dongting Lake National Nature Reserve and the surrounding area of Chenglingji outlet, with the lowest overall microplastic abundance.

Overall, microplastics in Dongting Lake show the spatial distribution characteristics of "estuaries higher than outlet, human activity-intensive areas higher than ecological reserves", which directly confirms that land-based input from inflow runoff is the dominant factor of microplastic pollution in Dongting Lake [48].

4.2. Spatial Differences in Occurrence Characteristics

There are obvious differences in the morphology, particle size and polymer composition of microplastics among the three major lake regions, which are highly matched with the types of human activities and industrial structure in each lake region, and have clear indicative significance for pollution sources [49].

In terms of morphological characteristics, the proportion of fibrous microplastics in sediments of South Dongting Lake is as high as 75.5%, significantly higher than that of West Dongting Lake (61.5%) and East Dongting Lake (73.1%), which is directly related to the intensive textile industry and aquaculture activities in this area. The proportion of fragment microplastics in East Dongting Lake reaches 24.7%, the highest in the whole lake, which is mainly driven by the intensive shipping activities at Chenglingji Port. The proportion of granular microplastics in West Dongting Lake reaches 18.8%, the highest in the whole lake, which is closely related to the extensive agricultural planting and agricultural plastic film input in this area [1]. The morphological proportions of microplastics in water and sediments of the three lake regions are compared in **Figure 5**.

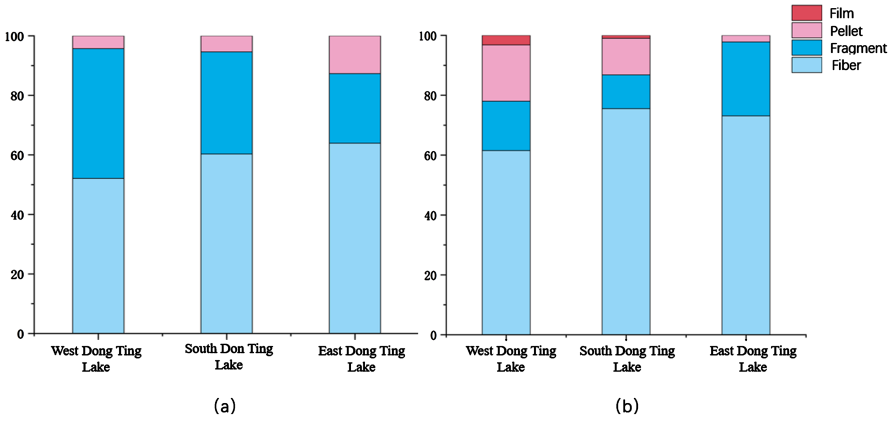


Figure 5. Morphological proportion of microplastics in water and sediments of the three major lake regions of Dongting Lake.

In terms of particle size distribution, the three lake regions show significant hydrodynamic sorting effect. The proportion of microplastics smaller than 0.5 mm in sediments of East Dongting Lake is as high as 74.2%, the highest in the whole lake; that in South Dongting Lake is the lowest, only 51.6%, but the proportion of 1.0 - 2.0 mm particles is significantly higher than that in other lake regions.

This pattern is dominated by the west-to-east confluence pattern of Dongting Lake: large-sized microplastics with high density have fast settling velocity, and

settle near the estuaries of West and South Dongting Lake, making it difficult to migrate over long distances; while small-sized microplastics have strong suspension capacity and can migrate eastward with runoff to be enriched in East Dongting Lake [50]. The particle size proportions of microplastics in the three major lake regions are presented in **Figure 6**.

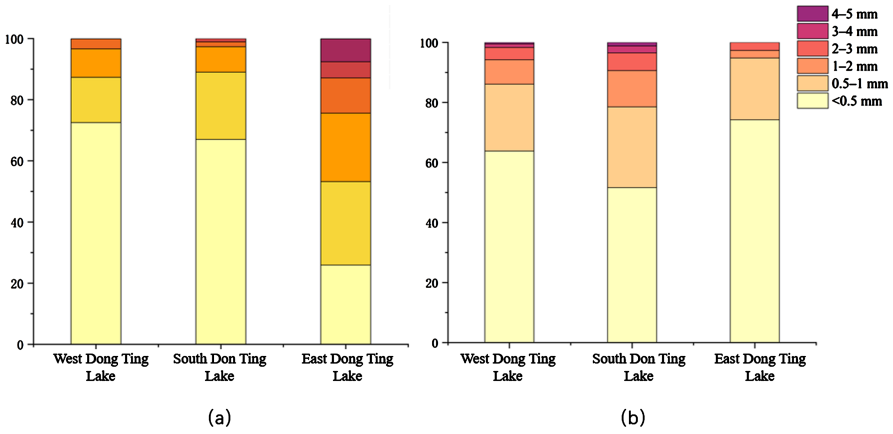


Figure 6. Particle size proportion of microplastics in water and sediments of the three major lake regions of Dongting Lake.

In terms of polymer composition, the proportion of polyamide (PA) in sediments of South Dongting Lake reaches 22.1%, the highest in the whole lake, which fully matches the extensive use of fishing nets and breeding ropes in aquaculture in this area. The proportions of polyethylene (PE) and polypropylene (PP) in West Dongting Lake are significantly higher than those in other lake regions, confirming that agricultural non-point source input is the core pollution source in this area. The proportion of polyvinyl chloride (PVC) in East Dongting Lake is the highest in the whole lake, which is highly consistent with the intensive shipping activities in this area [50]. The polymer composition differences among the three lake regions are intuitively shown in **Figure 7**.

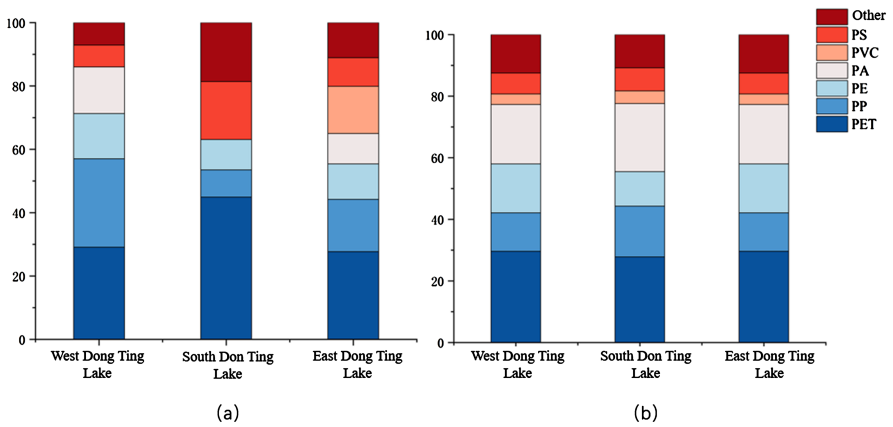


Figure 7. Polymer proportion of microplastics in water and sediments of the three major lake regions of Dongting Lake.

4.3. Brief Analysis of Influencing Factors for Spatial Distribution

Land-based anthropogenic input is the basic controlling factor for the spatial differentiation of microplastics in Dongting Lake. West Dongting Lake receives upstream inflows from the three outlets of the Yangtze River as well as the Yuan and Li rivers, with a large amount of land-based microplastics flowing into the lake area along with inflow runoff, resulting in the largest pollution input load. South Dongting Lake receives tail water from the Xiang and Zi rivers, superimposed with local production and domestic discharge, with medium pollution load. For East Dongting Lake, on the one hand, under the management of the national nature reserve, local new anthropogenic input is limited; on the other hand, microplastics can emigrate into the main stream of the Yangtze River along with Chenglingji runoff, so the overall abundance is the lowest. The high concentration of microplastics in major estuaries further indicates that land-based runoff input in the basin is the main way for microplastics to enter Dongting Lake.

River-lake hydrodynamic conditions further amplify the internal spatial heterogeneity of the lake area. The overall west-to-east flow direction of Dongting Lake produces obvious hydraulic sorting effect: microplastics with high density and large particle size settle preferentially near the estuaries; while fibers and small-sized microplastics have good suspension performance and can migrate long distances eastward with water flow.

Meanwhile, the seasonal hydrological feature of "forming a lake in flood season and exposing shoals in dry season" causes dramatic water level fluctuations within the year, which drives the dynamic source-sink transformation of microplastics among water, shoals and sediments: in flood season, microplastics in water are retained in sediments as water level drops; in dry season, disturbance resuspends sediment microplastics back into water, further reshaping the spatial distribution pattern of microplastics in the lake area.

Combined with occurrence characteristics, it can be identified that textile and urban domestic sewage, agricultural non-point sources, aquaculture and inland shipping are several potential pollution sources of Dongting Lake. Limited by the multi-source integrated dataset, this study only carries out qualitative source identification, and cannot obtain the quantitative contribution proportion of each pollution source.

5. Discussion

5.1. Comparison with Similar Lakes in the Middle and Lower Reaches of the Yangtze River

Through standardized integration of published in-situ measurement literatures, this study obtained the baseline of microplastic pollution in Dongting Lake: the sample-weighted average abundance of microplastics in surface water is 1700 items/m^3, and the sample-weighted average abundance in sediments is 610 items/kg (dry weight). Overall, microplastic pollution in Dongting Lake is at a medium to high level among freshwater lakes in the middle and lower reaches of the Yangtze River.

Horizontal comparison with similar lakes in China shows that the abundance of microplastics in water of Poyang Lake, another river-connected lake, is slightly higher than that of Dongting Lake, which is related to the larger population size and stronger pollution input load of the Poyang Lake Basin. The abundance of microplastics in water of Chaohu Lake, a closed lake, is significantly lower than that of Dongting Lake. In terms of sediments, the abundance of microplastics in Dongting Lake is basically in the same order of magnitude as Taihu Lake and Hongze Lake.

As a typical river-connected lake, Dongting Lake receives dual inflows from the Xiang, Zi, Yuan and Li rivers as well as the three outlets of the Yangtze River, with more input pathways of land-based pollutants in the basin and higher pollution supply intensity than closed lakes. Meanwhile, the hydrological condition of river-lake connection allows part of microplastics to be exported to the main stream of the Yangtze River through Chenglingji, which alleviates the cumulative load in the lake to a certain extent. This is also an important feature that distinguishes river-connected lakes from closed lakes.

However, it should be noted that there are differences in sampling equipment, pretreatment and detection methods among different lake studies. Cross-lake comparison can only reflect the relative pollution level, and it is difficult to achieve accurate comparison of absolute values.

5.2. Cause Analysis of Occurrence Characteristics

The integration results of this study show that fibers are the dominant morphology of microplastics in Dongting Lake, and small-sized particles smaller than 0.5 mm account for a prominent proportion. There are obvious medium differentiation characteristics in morphology, particle size and polymer composition between water and sediments, and there are also certain differences in physical and chemical composition among different lake regions.

Fibrous microplastics dominate the whole lake, which is mainly related to the discharge of textile industrial wastewater in the basin and the input of synthetic fibers from domestic washing into water bodies with sewage. Fibrous substances have large length-diameter ratio and strong suspension capacity, and are easier to be transported over long distances with runoff, hence a higher proportion in surface water. Granular microplastics have higher overall density and are more prone to gravity settling, resulting in a significantly higher proportion of granular microplastics in sediments than in water.

The high proportion of small-sized microplastics across the whole lake reflects the characteristics of long-term environmental aging and fragmentation of microplastics in the lake area. After entering the water environment, plastic products gradually break down under the combined action of ultraviolet radiation, hydraulic shear disturbance and biodegradation, continuously generating small-sized microplastics. Small-sized microplastics have large specific surface area, which are easy to adsorb and agglomerate with suspended particles and algal flocs in water,

increasing the equivalent density and accelerating the settling process, thus resulting in significant enrichment in sediments.

The differences in physical and chemical characteristics of microplastics among the three major lake regions correspond to the types of human activities around each lake region. The relatively high proportion of granules, PE and PP in West Dongting Lake is related to the input of plastic film and plastic packaging waste from agricultural planting activities in the region. The high proportion of PA and blue microplastics in South Dongting Lake reflects the potential impact of aging and shedding of aquaculture fishing nets and ropes. The relatively higher proportion of fragments and PVC in East Dongting Lake is associated with regional shipping activities. The above inferences are obtained based on the occurrence characteristics integrated from multi-source literatures, which need to be further verified by in-situ monitoring under unified conditions.

Combined with color characteristics, the widespread detection of transparent microplastics indicates the contribution of daily necessities plastic input; the high proportion of blue microplastics can be used as an important indicator for aquaculture input; the relative enrichment of black microplastics in East Dongting Lake can also be used as an auxiliary basis for judging shipping-related pollution.

5.3. Research Limitations and Prospects

This study carries out multi-source data integration analysis based on published literatures, and there are still certain limitations. There are differences in sampling, pretreatment and detection conditions among the second-hand literatures used in the study, and the spatial distribution of sampling points is unbalanced. The existing public data are difficult to distinguish the hydrological differences between flood season and dry season, and can only carry out qualitative pollution source identification, but cannot realize quantitative analysis of pollution sources.

In view of the existing shortcomings, further deepening can be carried out from three aspects in the follow-up: First, build a standardized long-term monitoring system. Unify the technical standards of microplastic sampling, pretreatment and detection, establish a normalized monitoring network across the whole Dongting Lake, carry out synchronous observation in multiple hydrological periods, and systematically reveal the spatiotemporal evolution law of microplastics under the influence of hydrological rhythm. Second, promote quantitative source tracing research of pollution sources. Carry out field in-situ measurement, combined with source analysis models, accurately quantify the contribution proportion and input pathways of each pollution source, realize the upgrade from qualitative identification to quantitative identification, and provide basis for precise pollution control. Third, improve multi-medium ecological correlation investigation, supplement the observation of microplastic bioaccumulation in aquatic organisms, and provide scientific support for zonal management of microplastics, drinking water source protection and aquatic ecological restoration in Dongting Lake Basin.

6. Conclusions

1) Microplastics are widely detected in water and sediments of Dongting Lake. The abundance of microplastics in surface water of the whole lake ranges from 900 to 2500 items/m^3, with a sample-weighted average of 1700 items/m^3; the abundance of microplastics in surface sediments ranges from 20 to 1200 items/kg (dry weight), with a sample-weighted of 610 items/kg (dry weight). Compared with similar lakes in the middle and lower reaches of the Yangtze River, the overall microplastic pollution in Dongting Lake is at a medium to high level. The dominant morphology of microplastics in the whole lake is fiber, the dominant particle size is concentrated in the range of <0.5 mm, the dominant polymers are PET, PE, PP and PA, and the main colors are transparent and blue.

2) There are obvious medium differences in the occurrence characteristics of microplastics in Dongting Lake. Affected by settling dynamics and polymer density, the proportion of fibrous microplastics in water is higher; small-sized and granular microplastics have significant enrichment effect in sediments; high-density polymers are more likely to accumulate in sediments, while low-density polymers tend to suspend and migrate in water. Seasonal water level changes in Dongting Lake drive the dynamic source-sink transformation of microplastics between water and sediments.

3) The spatial distribution of microplastics in Dongting Lake presents a significant gradient pattern of "West Dongting Lake > South Dongting Lake > East Dongting Lake". The estuaries of inflowing rivers are high-value pollution areas, while the Chenglingji outlet and East Dongting Lake Nature Reserve are low-value pollution areas. The spatial variation trends of microplastics in water and sediments are basically consistent. There are differences in morphology, particle size and polymer composition of microplastics among different lake regions, which can indirectly reflect the pollution characteristics of regional human activities such as agriculture, aquaculture and shipping.

4) The spatial pattern of microplastics in Dongting Lake is jointly driven by land-based anthropogenic input and hydrodynamic conditions of the river-connected lake. Land-based runoff input is the main way for microplastics to enter the lake area; the west-to-east flow direction and the seasonal hydrological process of "forming a lake in flood season and exposing shoals in dry season" produce hydraulic sorting effect, further amplifying the internal spatial heterogeneity of the lake area. Textile and urban domestic sewage, agricultural non-point sources, aquaculture and inland shipping are potential pollution sources of Dongting Lake.

Author Contributions

Conceptualization, X.L.Q.; methodology, X.L.Q.; software, X.L.Q.; validation, H.T.X., Y.W., and X.L.Q.; formal analysis, X.L.Q; investigation, X.L.Q.; resources, X.L.Q.; data curation, X.L.Q.; writing—original draft preparation, X.L.Q; writing—review and editing, X.L.Q.; visualization, X.L.Q.; supervision, X.L.Q.; All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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