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Distribution Characteristics and Source Analysis of Microplastics in Urban Freshwater Lakes: A Case Study in Songshan Lake of Dongguan, China

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Abstract: Current studies on microplastic pollution mainly focus on marine systems. However, few studies have investigated microplastics in an urban lake. This research intends to use an urban lake (Songshan Lake) as an example to explore the pollution characteristics of microplastics and use the principal component as well as the heat map analysis to discuss the relationships between different shapes of microplastics. According to this study, the average abundance of microplastics in the surface water and surface sediments of Songshan Lake were, respectively, 2.29 ± 0.98 items/m^3 and 244 ± 121 items/kg; thin films were the major microplastics in both media; transparent this type of color has the most microplastic content. The particle size of microplastics was mainly 0.18–0.6 mm (43.3%) in surface water and 1–2 mm (48.3%) in surface sediments. The composition included five polymers: polyethylene (PE), polypropylene (PP), polypropylene–polyethylene copolymer (PP–PE copolymer), polystyrene (PS), and polyvinyl chloride (PVC), among which PE (47%) and PP (36%) were the main components. Principal component analysis (PCA) showed that there was a positive correlation among the four shapes of microplastics: films, fragments, foams, and fibers. The heat map analysis showed that the same category of shape distribution features may be similar for each sampling site.

Keywords: microplastic; urban lake; sediment; water; source analysis

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1. Introduction

Since mass production began in the 1950s, the global production of plastic dramatically increased from 0.5 million tons per year in 1960 to 367 million tons in 2020 [1]. Humans increasingly enjoy the convenience brought by the widespread use of plastic products, which at the same time has produced some environmental problems [2]. In particular, pollution by microplastics (those plastic fragments or films below 5 mm in diameter) decomposed from plastics products in the environment has become a growing environmental concern in recent years [3–5].

Microplastics have become globally pervasive, affecting aquatic [6,7], atmospheric [8,9], and terrestrial environments [10,11] as well as biota [12]. Owing to their small size and light weight, contaminated microplastics can move with the flow of water and air and be transported to different environments [13], posing a serious threat to the ecological balance [14]. The marine environment is the first area of concern for microplastic pollution and the most polluted site [15]. Marine waters are an important sink for microplastics, with about 10–15 million tons of plastic waste being discharged directly or indirectly into marine waters globally each year, the vast majority of which are microplastics [16]. Additionally, the terrestrial environment is also home to a large number of microplastics [17]. Previous studies have shown that although the discharge rate of microplastics after treatment by wastewater treatment plants is low, most of the microplastics are sloughed off in the sludge generated by these plants, which is often used as compost and thus enters the terrestrial environment [18]. So far, there are not many studies on microplastic pollution in lakes, and most of them were focused on remote plateau lakes [19], remote alpine lakes [20,21], Yangtze River delta lakes [22,23], middle Yangtze River lakes [24], and inland lakes [25], among others. However, relatively little information is available on the characterization and source analysis of microplastic pollution in urban freshwater lakes, especially in China, the largest producer of plastics around the world [1].

Lakes are nodes of river runoff and important water sources for human survival; important places for aquatic life to flourish. At the same time, lakes are also an important part of the terrestrial hydrosphere and have the special function of maintaining regional ecological balance and reproducing biodiversity. Lakes are relatively closed environmental systems and the more stable water flow conditions are conducive to the slow decomposition and accumulation of microplastics in lakes compared to rivers or other water bodies [26]. Moreover, cities provide a variety of sources of microplastics in spatially concentrated areas that are easily transported to other ecosystems [27].

Thus, in this study, microplastics were extracted from the surface water and sediments of the urban lake (Songshan Lake), and the pollution characteristics and distribution range of microplastics were explored. In addition, sources analysis of microplastics were conducted according to their physicochemical properties, and the relationship between different shapes of microplastics was studied.

2. Materials and Methods

2.1. Study Areas and Sampling Collection

As an urban inland lake, Songshan Lake (22°52′15.33″–22°55′52.42″ N, 113°50′57.86″–113°53′58.36″ E) is located in the areas of Dalang Town, Dalingshan Town, and Liaobu Town. With a water area of 8 km^2, Songshan Lake is an area of a good natural environment. Sample collection was conducted in March 2018. The sample collection method could be found in our previous paper described by Tan et al. [28]. The sampling routes were selected from upstream to downstream (i.e., W1→W2, W3→W4, W5→W6, and W7→W8) of the surface water of Songshan Lake (Figure 1 and Table 1). A #13# conical plankton net with a mesh size of 0.112 mm (opening diameter 20 cm) was used to collect surface water samples from Songshan Lake's upper water column (depth ~20 cm). Surface water samples were collected in triplicate from a boat traveling at a constant speed of 3 km/h. Each site was trawled for a distance of approximately 1 km and a flowmeter (PS-TL, China) was attached to the mouth of the net to measure the amount of water that had been filtered. Sediment samples were taken from six sampling sites in the surface layer of the surface sediments of Songshan Lake (i.e., S1, S2, S3, S4, S5, and S6) (Figure 1 and Table 1). A stainless steel shovel and a 20 × 20 cm wooden frame with a height of 2 cm were used to randomly sample three sediments from each site to a depth of 2 cm, which was then mixed into one sample from each site using an aluminum foil bag.

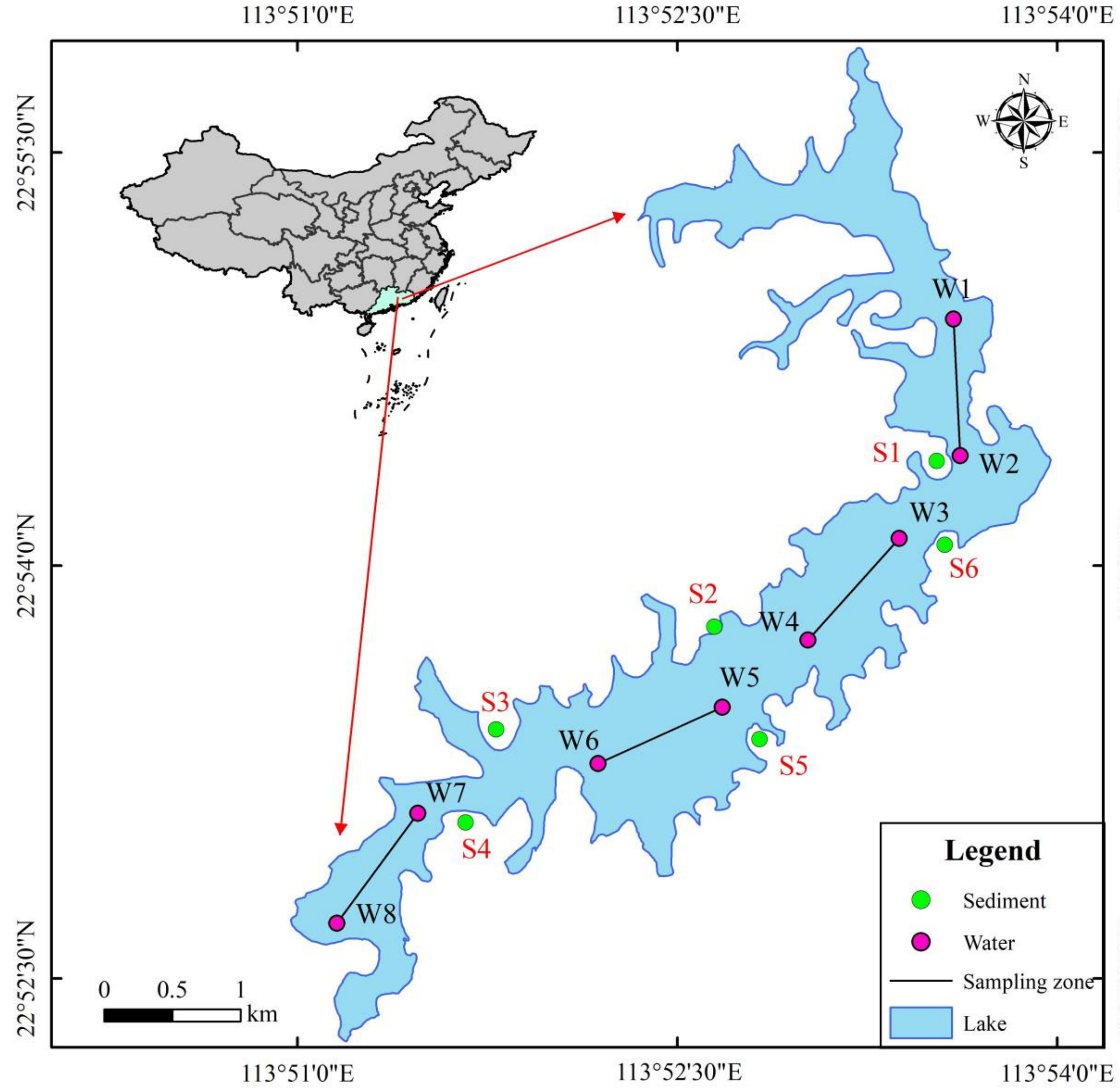

Figure 1. The geographic location of sampling sites from the surface water and the surface sediments of Songshan Lake.

Table 1. Location of sampling sites in the studied areas.

Sampling Sites	Latitude	Longitude
W1	22°54′55.28″ N	113°53′33.95″ E
W2	22°54′21.57″ N	113°53′37.88″ E
W3	22°54′6.61″ N	113°53′22.3″ E
W4	22°53′45.59″ N	113°52′57.27″ E
W5	22°53′31.66″ N	113°52′34.35″ E
W6	22°53′19.56″ N	113°52′1.44″ E
W7	22°53′6.04″ N	113°51′28.12″ E
W8	22°52′40.61″ N	113°51′6.41″ E
S1	22°54′21.21″ N	113°53′31.79″ E
S2	22°53′47.08″ N	113°52′38.4″ E
S3	22°53′32.24″ N	113°52′2.7″ E
S4	22°53′4.89″ N	113°51′36.21″ E
S5	22°53′25.28″ N	113°52′34.8″ E
S6	22°54′2.85″ N	113°53′41.28″ E

2.2. Pretreatment of Samples

The samples were collected with plankton nets from the surface waters and filtered residues were rinsed with deionized water, then immediately preserved in glass containers; these were then transported to the lab for analysis [29]. A tiered sieve system with mesh sizes of 10, 30, 80, and 240 was used to respectively separate the particles into four particles sizes (i.e., 0.112–0.18, 0.18–0.6, 0.6–2, and 2–5 mm). Glass containers in which the rinse solution was stored were rinsed a minimum of three times, and the rinse solution was then transferred to the dispensing sieve. Because of the aperture limitation of the sieve, particles smaller than 0.112 mm were excluded from pretreatment, while particles larger than 5 mm were too large to be considered microplastics ($\leq$5 mm) and manually removed. Additionally, we filtered samples with sizes of 0.112 to 0.6 mm into glass microfiber filters (Whatman GF/B, 47 mm in diameter with a 1 μm pore size) using vacuum pumps. Deionized water was used to rinse the walls of the filter unit multiple times, and the samples were transferred to filter paper for further filtration. The filter paper was transferred to a Petri dish, where the sample was dried at a constant temperature of 50 °C for more than 48 h followed by analysis. Samples with sizes ranging from 0.6 to 2 and 2 to 5 mm were manually transferred using nonmagnetic tweezers to clean glassware.

After all sediment samples were transferred to the laboratory, they were dried at a constant temperature of 50 °C for at least 48 h. A density separation method was used to extract microplastics from each sediment sample [30]. Using a glass rod, 200 mL of saturated ZnCl solution was stirred with the sediment in a glass beaker for 5 min. After standing for 2 h, an ultrasonic cleaner was used for 5 min to remove surface sand and adherents loosely adhered to the microplastics floating in the supernatant of the glass beaker [31,32]. Vacuum pumping was used to filter the supernatant through the glass microfiber filter (Whatman GF/B, 47 mm in diameter with a 1 μm pore size) after the mixture was stood overnight. Deionized water was used to rinse the walls of the filter unit multiple times, and the sample was transferred to filter paper for further filtration. The filter paper was transferred to a Petri dish, where the sample was dried at a constant temperature of 50 °C for more than 48 h and then stored in the Petri dish. To exclude external environmental interference and reduce experimental error, lab coats were worn throughout the experimental process. All glass containers and filtration devices were rinsed thoroughly with ultrapure water and then dried at 200 °C for at least two hours before use [33]. Additionally, experimental blank samples were also prepared to ensure that no other microplastics had been added during the pretreatment and analytical processes.

2.3. Microscopic Imaging and μ-FTIR Analysis

After pretreatment, the particles on the filters were analyzed by a digital microscope (Dino-Lite, AM3011T) using Dino-Capture 2.0 software at a magnification of 30–50 times [34,35]. Images were captured with a handheld microscope connected to a computer. Based on the guidelines of the visual method [36], the samples were observed and statistically classified by the visual observation method. Using an infrared microscope (NicoletiN10, Thermo Fisher, Bridgewater, MA, USA) equipped with a deuterated triglycine sulfate (DTGS) detector, micro-Fourier-transform infrared (μ-FTIR) analysis was conducted on the suspected samples [37], allowing the samples to be detected non-destructively. In the reflectance mode, spectra in the range of 4000–500 cm^{-1} were collected, and the acquisition time for each measurement was 16 s [38]. The surfaces of each suspected sample were detected [39] in two separate spots so that a higher degree of similarity could be obtained between the spectra. With OMNIC software, the resulting spectra were automatically compared to Thermo Fisher Scientific databases without post-processing and transformation [40]. In order to calculate the average abundance of microplastics in the water, the number of particles in the plankton net after sampling was used along with the distance from the collection station and the open area of the net; the abundance was expressed as items/m^3. The microplastic abundance in each sediments site was determined using the number of microplastic particles identified in three replicate samples and is expressed as items per kilogram of dry sediment (items/kg). The calculated concentrations were expressed as mean values with standard deviations (SD).

2.4. SEM/EDS Analysis

Scanning electron microscopy combined with energy-dispersive X-ray spectroscopy (SEM/EDS) (CLARA, TESCAN, Prague, Czech)was performed to understand the characteristics of the surfaces and the type of metal accumulated in the microplastics after ultrasonic cleaning [33]. The samples were identified as microplastics by μ-FTIR analysis and then coated with platinum film and imaged by field emission scanning electron microscopy (JSM-6510, JEOL, Thermo Fisher, Bridgewater, MA, USA) at 20 KeV. The microplastics were analyzed using EDS (X-Act, Oxford Instruments, Prague, Czech) for their compositional elements. Since the surface morphology of the microplastic samples undergoing physical and chemical weathering was not smooth, at least three relatively rough and smooth sites on the surface of each sample to be tested were selected for surface morphology and elemental composition analysis.

2.5. Data Analysis

Maps of the spatial distribution were produced using ArcGIS 10.2. SPSS version 26 was used for statistical analysis. The data were tested statistically for normality using Shapiro–Wilk (S–W) tests. Two independent samples of surface sediment and surface water were assessed for significant differences ($p > 0.05$) in the abundance of microplastic particles using the Mann–Whitney (M–W) U test. Data processing was conducted using Origin 2020. The relationship between different polymer shape types and sampling points was analyzed by a multivariate statistical technique, principal component analysis (PCA). Specifically, find out which sampling sites contribute the most microplastic shapes to the overall distribution. The PCA with varimax rotation is used for dataset interpretability while minimizing the loss of information, and to classify the relationships among the variables [41]. Cluster analysis identified study areas that had similar characteristics of pollution and sources of pollution using the systematic clustering of sampling sites.

3. Results and Discussion

3.1. Composition of Microplastics

The surface water and surface sediments of Songshan Lake contained five types of microplastics: polyethylene (PE), polypropylene (PP), polypropylene–polyethylene copolymer (PP–PE copolymer), polystyrene (PS), and polyvinyl chloride (PVC) (Figure 2a). As illustrated in Figure 2b, PE (47%) and PP (36%) were the most abundant types of microplastic among the identified samples, followed by PS (9%), PP–PE copolymer (6%), and PVC (2%). Polymers detected in this study were similar to those found in previous studies carried out in Taihu Lake [23] and urban lakes around Wuhan [25]. Identified polymer samples were verified by characteristic peaks in a specific infrared spectrum wave (Figure 2a). PP, PE, PS, and PVC are widely used in production and life because of their low price, large production volume, wide application, and wide influence range. PP and PS are mainly used for agricultural films, packaging materials, and fishing gear, while PVC is mainly a raw material for plastic films and is also widely used in home construction products and fireproof materials [42]. As a consequence, in aquatic environments, plastic products used in aquatic aquaculture and agricultural farming as well as in everyday products, including shipping materials and takeout packaging, among others, have the potential to cause microplastic pollution [43]. Surface water contains a large amount of accumulated microplastics. The density of polymeric materials, e.g., polypropylene (0.85–0.93 g/cm^3) and polyethylene (0.91–0.93 g/cm^3), is usually less than that of water (1 g/cm^3) [44,45]. Because of this, they can float on the surface of water regardless of their size or shape and are easily able to spread across the surface [45]. Additionally, fast water flow might affect their distribution [46]. It should be noted that density is not the only factor that affects microplastic distribution in aquatic environments. In surface water, it is common to find polymers that have higher densities than water, such as PS (1.05 g/cm^3) and PVC (1.38 g/cm^3) [47,48]. This may be because of change in the density of plastics made with the corresponding polymers could affect the volume, shape, and quality of the plastics, resulting in a certain buoyancy on the surface of the water [49]. This enables microplastics to accumulate on the surface water. Notably, PVC was not detected in the surface water of Songshan Lake and was only present in the surface sediments of Songshan Lake in this study, which is likely because PVC has a higher density than fresh water. However, PVC has been reported in studies of other aquatic environments such as Qinghai Lake [50] and Feilaixia Reservoir [28] (Table 2); this may be due to the adhesion of PVC to some low-density suspended solids, allowing it to float in surface waters. Copolymers were found to be present in this study (Figure 2a), and the southern shore of Lake Victoria contained the same species [51]. It has been shown that the copolymerization processes can lead to the creation of novel materials with enhanced properties even though there are relatively few reports on copolymers [52].

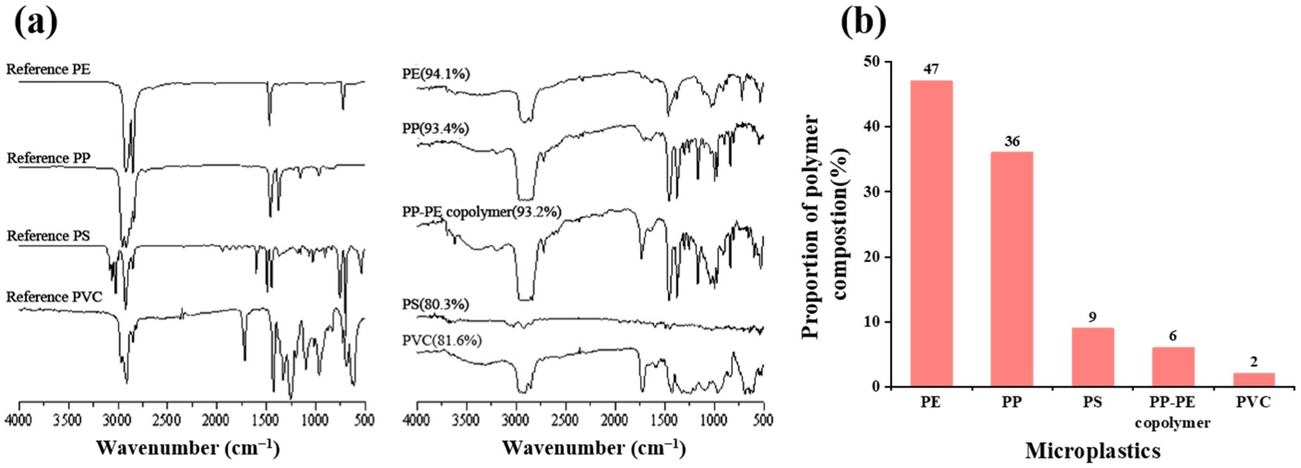

Figure 2. (**a**) Match between identified polymer and standard spectra; (**b**) Proportions of major components of microplastics in surface water and surface sediments of Songshan Lake.

Table 2. Microplastics in various aquatic environments and their compositions.

Region	Medium	Major Polymer	Reference
Qinghai Lake	Water, Sediment	PE, PP, PS, PVC, Nylon, PET, PC, EVA	[50]
Feilaixai Reservoir	Water	PE, PP, PS, PVC, PET	[28]
Xiangxi Bay	Water, Sediment	PE, PP, PS, PET	[53]
Huron Lake	Sediment	PE, PP, PET	[54]
Beijiang River	Sediment	PE, PP, PP-PE copolymer	[34]
Songshan Lake	Water, Sediment	PE, PP, PS, PP-PE copolymer, PVC	Present study

3.2. Abundance of Microplastics

According to typical observational criteria [36], the visual observation method was used to complete the preliminary statistics of sample abundance. Then, combined with the results of infrared spectrum analysis, i.e., the proportion of microplastics in surface water and surface sediment samples (98.6% and 95.2%, respectively), the abundance of microplastics in the lake surface water and surface sediments of Songshan Lake was calculated (Figure 3a,b). The surface water of Songshan Lake had an average abundance of 2.29 ± 0.98 items/m^3. Individually, the microplastic abundances of the four sampling routes (W1→W2, W3→W4, W5→W6, and W7→W8), were 1.94 ± 0.60, 1.91 ± 0.45, 1.58 ± 0.16, and 3.72 ± 0.68 items/m^3, respectively. The average abundance of microplastics in the surface sediments of Songshan Lake was 244 ± 121 items/kg. Specifically, the abundance of microplastics from the six sampling points (S1, S2, S3, S4, S5, and S6) was

161 ± 24, 222 ± 35, 139 ± 42, 300 ± 60, 461 ± 84, and 183 ± 33 items/kg, respectively. The greatest abundance of microplastics in the surface water appeared in the lower part of Songshan Lake (W7→W8), while the lowest was observed in the middle and lower section (W5→W6). The abundance of microplastics in the upper part (W1→W2) was similar to that in the middle and upper segments (W3→W4). The highest abundance of microplastics was found in the middle-lower segment (S5) in the surface sediments of Songshan Lake, the lowest abundance was found in the middle-lower segment (S3), and the middle abundance was concentrated in the middle-upper segment (S2 and S6). From the collation, the abundance of microplastics in surface water and sediment on the lake shoreline did not show an obvious spatial distribution pattern. The abundances of microplastics at different sampling sites were not significantly different ($p > 0.05$).

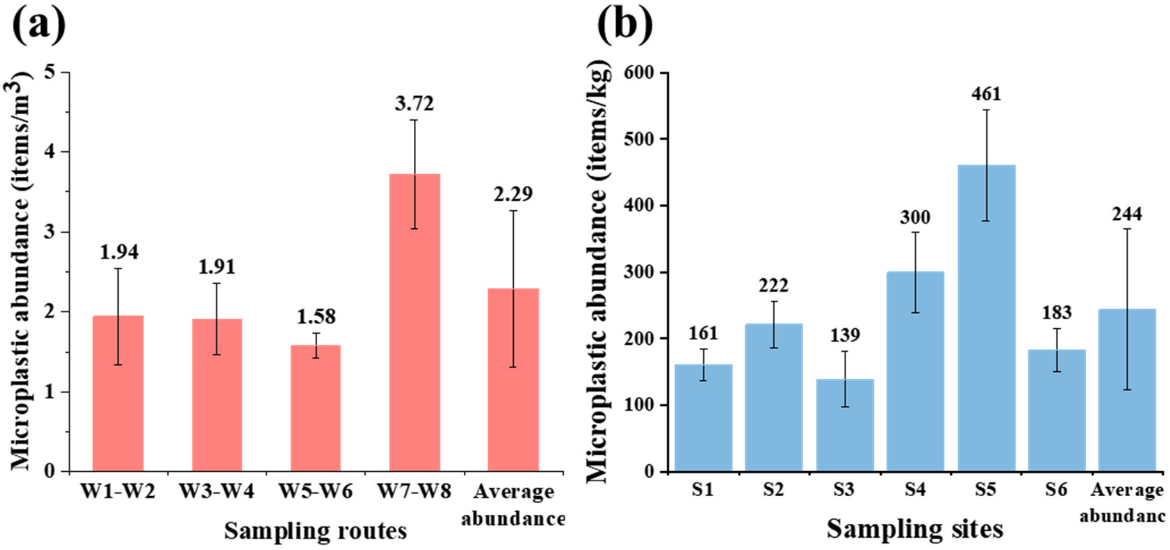

Figure 3. The abundance of microplastics collected from the surface water (**a**) and the surface sediments (**b**) of Songshan Lake.

In addition to the regional hydrology, wind direction and other natural factors would affect the spatial distribution of microplastics; the degree of urbanization and regional population density were also important factors affecting the degree of microplastic pollution in this region [55]. As a tourist attraction, Songshan Lake attracts a large number of tourists every year. Therefore, the behavior of tourists and the environmental management and treatment measures of the scenic area are closely related to microplastic pollution in the Songshan Lake area. Considering the uncertainty of tourist behavior and the hysteresis of environmental governance, this may be one of the reasons why the abundance of microplastics in the Songshan Lake area did not show obvious spatial distribution. It is important to compare microplastic abundances across different publications with some caution since there are considerable differences in sampling, sample preparation, and visual assessment methods [56,57]. As a result, we selected studies that quantified microplastics in freshwater lakes around the world using similar measurement units (Table 3). It can be seen that the abundance of microplastics detected in the surface waters of Songshan Lake is higher than in Lake Hovsgol in Mongolia [20] and 29 Great Lakes tributaries, USA [58], but relatively lower than those observed in the Lake Dongting, Lake Hong [24], and 20 main lakes in Wuhan [25] in China, which may be related to factors such as economy, population, wind direction, hydrodynamic condition and source loading [19,50]. Overall, the level of microplastics' concentration in Songshan Lake was moderate.

Table 3. Comparison of microplastic abundance in freshwater lake studies around the world. Avg. means the average abundance of microplastics.

Locations	Abundance	References
Surface Water		
Great Lakes, USA	7–18.5 items/L	[59]
Twenty-nine tributaries, USA	1.9 items/m^3 (Avg.)	[58]
Bolsena Lake, Italy	2.51 items/m^3 (Avg.)	[60]
Chiusi Lake, Italy	3.02 items/m^3 (Avg.)	[60]
Hovsgol Lake, Mongolia	0.12 items/m^3 (Avg.)	[20]
Iseo Lake, Italian	8 items/L	[21]
Dongting Lake, China	1191.7 items/m^3 (Avg.)	[24]
Hong Lake, China	2282.5 items/m^3 (Avg.)	[24]
Poyang Lake, China	5–34 items/L	[12]
20 lakes of Wuhan, China	1660–8925 items/m^3	[25]
Taihu Lake, China	1.7–8.5 items/L	[23]
Songshan, China	2.29 items/m^3 (Avg.)	Present study
Locations	**Abundance**	**References**
Sediment		
Dongting Lake, China	180–693 items/kg	[61]
Poyang Lake, China	54–506 items/kg	[12]
Taihu Lake, China	460–1380 items/kg	[23]
Songshan, China	139–461 items/kg	Present study

3.3. Morphological Characteristics of Microplastics

Microplastics detected in the surface water and the surface sediments of Songshan Lake were in the shapes of films, fragments, foams, and fibers (Figure 4). The proportion of these four types of microplastics was, respectively, 60.7, 24.2, 3.9, and 11.2% in surface water (Figure 5a) and 49.2, 33.5, 5.4, and 11.9% in surface sediments (Figure 5b). Based on the morphological characteristics of microplastics, the source of microplastics found in the environment can be determined [62]. For example, fibrous microplastics may come in large part from clothing and textiles [63]. In addition, surface runoff and atmospheric deposition are also potential sources of plastic fibers in the environment [33,60]. These films and fragments were usually irregular in shape and had evident weathering traces (Figure 4), indicating that they likely originated from the breakdown of larger plastic products such as plastic bags after use or improper handling, and foam may come from expanded polystyrene products [48,64]. Therefore, morphological patterns of the microplastics suggest their origin from the breakdown of daily used plastic products such as packing materials, and containers, i.e., mainly from secondary sources. In the environment, plastics slowly degrade under high temperatures, wind, the currents of the water, and other natural forces, and migrate through lakes and atmosphere [42].

The size distribution of microplastics found in the surface water and the surface sediments of Songshan Lake is shown in Figure 5. Based on the size categories of microplastics in surface water, four main categories could be distinguished (2–5, 0.6–2, 0.18–0.6, and 0.112–0.18 mm); the most common distribution was 0.18–0.6 mm (43.3%) followed by 0.112–0.18 mm (38.1%) and 0.6–2 mm (12.4%), with the least common being 2–5 mm (6.2%) (Figure 5c). The microplastics in surface sediments can be classified into three different size ranges, i.e., 2–5 mm, 1–2 mm, and <1 mm, which accounted for 37.8, 48.3, and 13.9% of microplastics, respectively (Figure 5d). As in previous studies, the proportion of small microplastic particles (0.112–0.6 mm) accounted for the highest proportion of microplastics in the surface water, similar to what was observed in the Wei River [65], Three Gorges Reservoir [66], and Taihu Lake [23]. The high abundance of small microplastics in the surface water may be due to larger microplastics splitting into smaller particles [67]. It is worth noting that smaller microplastics are more capable of penetrating deeply into organs and causing more serious damage [68,69]. In addition, the proportion of microplastics with a particle size greater than 1 mm was higher in surface sediments than in surface water. This implies that a higher proportion of primary (i.e., as released into the environment) microplastic particles might be found in the surface sediments, whereas microplastic particles in surface water are more likely to be weathered and turn into secondary microplastic particles [70]. Larger particles in surface water can be more readily transported via convection than smaller ones [71]. Thus, larger microplastic particles are more likely to wash up on the lake shoreline [72]. Physical wave erosion in the surface area causes equally dense microplastics to wash from the surface sediments into the water. A variety of microplastics from different environmental settings have undergone varying degrees of chemical weathering, physical fragmentation, and biotic processing [73]. According to these results, the size of the microplastic particles explains the difference between water and sediment samples.

The Songshan Lake Basin contained a variety of microplastic samples. As shown in Figure 5, among the identified samples, the proportion of transparent (41%) plastic particles in the surface water was the highest, followed by black (17%), blue (16%), white (14%), red (8%), and green (4%). Among the surface sediments, transparent (32%) was the most abundant microplastic type, followed by black (19%), white (16%), blue (15%), red (12%), and green (6%). These results are consistent with those found by Di and Wang [66]. Microplastic particles in all water and sediment samples were mainly transparent (41 and 32%, respectively) (Figure 5e,f). Most microplastics found in the environment are characterized by this color [74], which may be the result of discoloration caused by weathering and sunlight exposure [63,75]. In addition, transparent microplastics may also come from fishing activities, as important fishing tools, including fishing lines and nylon nets, are colorless; it is likely that the colored microplastics we observed originated from colored plastic products commonly used in daily life, such as clothing, commodity packaging, and disposable plastic bags [24,76]. The diversity of the colors of microplastics indicates the diversity of their sources of contamination [25]. The fact that these microplastics were primarily in the shape of films could have also contributed to this result.

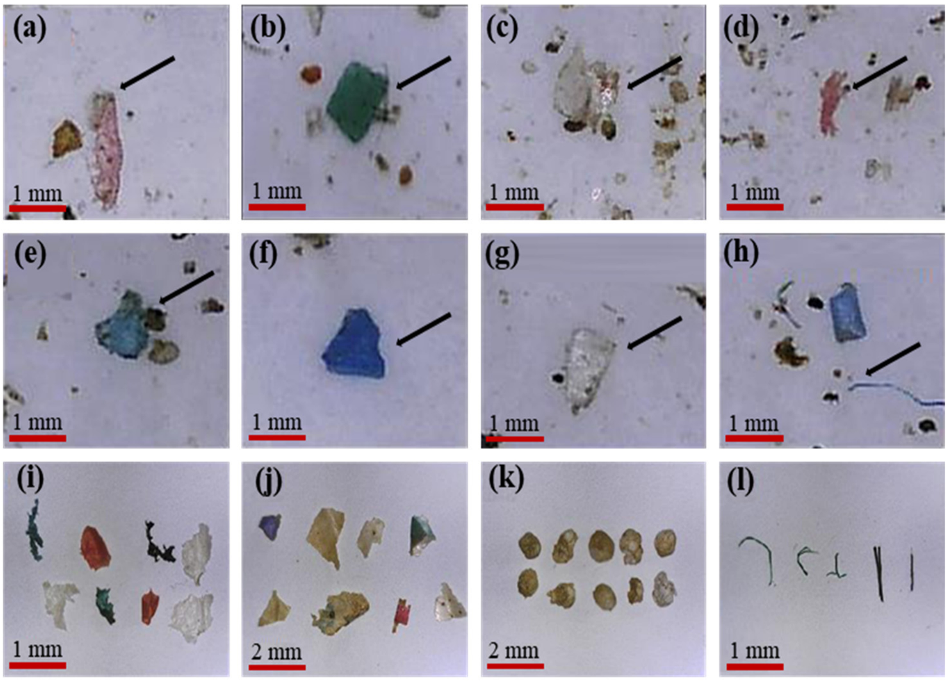

Figure 4. An overview of microplastic morphology: (**a**,**e**,**i**) film, (**b**,**f**,**j**) fragment, (**c**,**g**,**k**) foam, and (**d**,**h**,**l**) fiber.

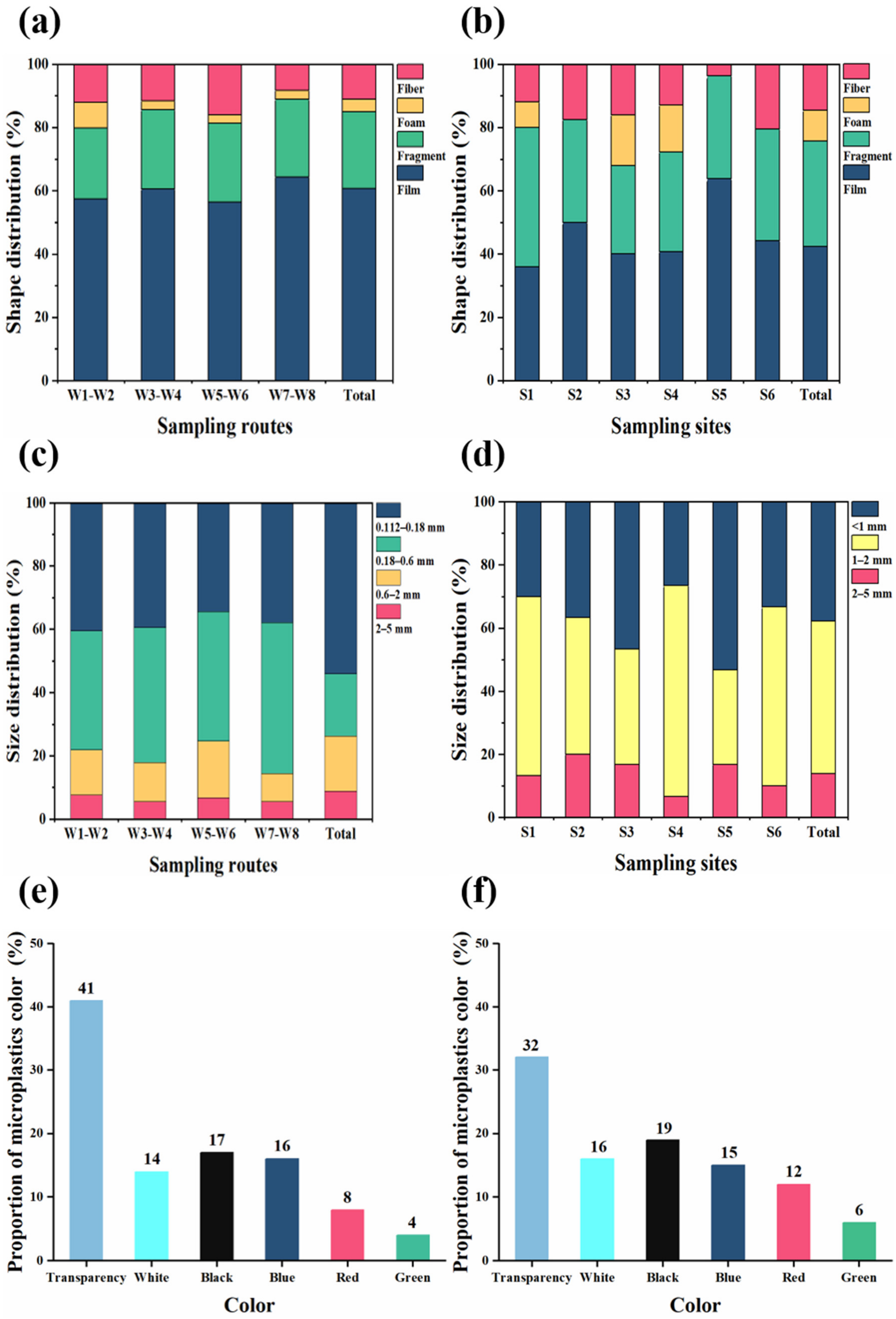

Figure 5. In surface water (**a**) and in surface sediments (**b**) of Songshan Lake, the relative proportions of different morphological shapes of microplastics were determined. Size distribution of microplastics in the surface water (**c**) and the surface sediments (**d**) of Songshan Lake. The proportion of microplastic color in the surface water (**e**) and surface sediment (**f**) of Songshan Lake.

3.4. Surface Textures

SEM images showed that microplastics in the surface water and surface sediments of Songshan Lake had undergone different degrees of physical and chemical weathering. There were six kinds of surface morphology: exfoliation, linear crack, granular oxidation, adhering particles, mechanical pit, and solution pit (Figure 6A). This was similar to the patterns observed in other lakes [54]. Consequently, the microplastics were likely to be formed by successive breakage of larger pieces of plastic, and their migration would be affected by factors such as water flow, wind, climate, and geography [19,47]. As confirmed by FTIR spectroscopy, the microplastics underwent chemical weathering in the environment. Our goal was to obtain higher matching and absorption peaks of the developed functional groups based on the FTIR spectra collected from two different positions of the surface of a single microplastic (Figure 2a). First, microplastics were identified by the higher degrees of similarity (94.1% for PE and 93.4% for PP) with the standard spectra. The absorption peaks near 1715 cm^{-1} and 3300 cm^{-1} corresponded to the carbonyl (C=O) and hydroxyl (–OH) groups, respectively, indicating that the plastic particles may be subjected to UV irradiation and oxygen in the environment, which results in photooxidation [77,78]. In addition, the adsorption capacities of microplastics with different types of polymers differ [79,80]. As a consequence, they typically contain other contaminants from the same environment, which they carry with them when they migrate. Further, it has been shown that the larger the surface area of an aged plastic particle, the greater it is porosity and adsorption capacity for toxic substances [81]. An analysis of the energy spectrum revealed a variety of metal elements adsorbing to the microplastic surface (Figure 6B). Consequently, composite environmental contamination will remain a persistent problem.

3.5. Sources of Microplastics

Multivariate statistical analyses were performed to better understand the morphological characteristics of the microplastics. For shape distribution, the four variables were analyzed using the PCA method (Figure 7a) [82]. The results of principal component analysis (PCA) indicate that two factors (PC1, PC2) described 96.28% of the total variance. The PCA on the microplastics shape type with respect to microplastic numbers showed that the first principal component (PC1) explained 82.83% of the variation in film, fragment and fiber; while PC2 explained 13.45% of the variation of foam. Meanwhile, the angle between all four variables was less than 90°, i.e., all four shape types of microplastics of film, fragment, foam, and fiber showed positive correlations with each other. They also revealed that films, fragments, and fibers were mainly distributed in W3→W4, W5→W6, and W7→W8. However, foams were mainly distributed in W1→W2. Based on the four variables, we clearly separated into two groups, and we used heat maps analysis to classify sampling sites with similar shape distributions (Figure 7b), in which all sampling points were divided into three main categories. The surface water sampling sites of Songshan Lake, S1, S2, S3, S4, S5, and S6, were the first category, the lakeside sediment sampling sites, W1→W2, W3→W4, W5→W6, were the second category, and the W7→W8 sampling sites were the third category. Based on the shape distribution characteristics of the same category, it can be inferred that the sources of pollution may be similar at each sampling point [42].

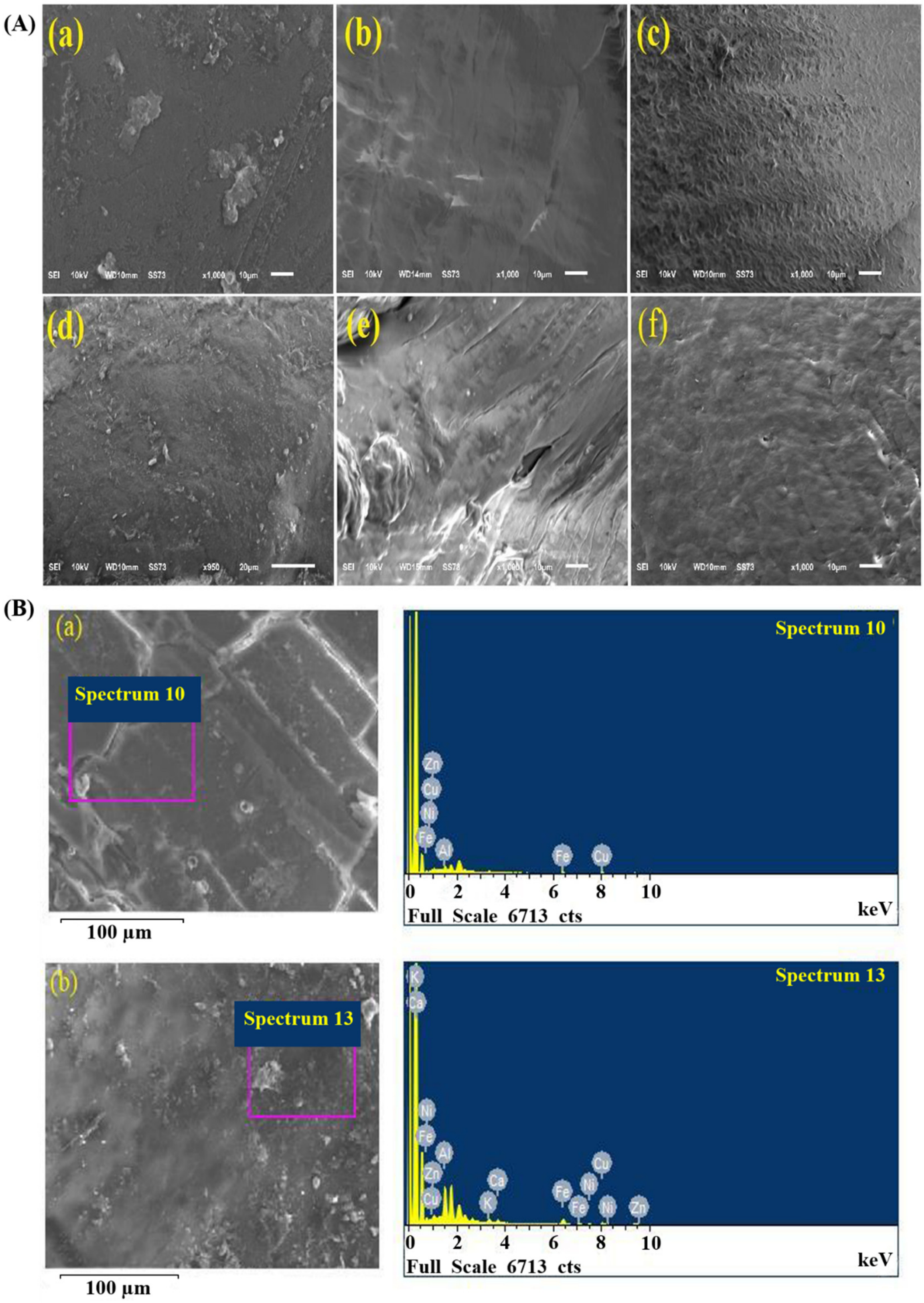

Figure 6. (**A**) SEM images of microplastics collected from the surface water and the surface sediments of Songshan Lake: (a) exfoliation; (b) linear crack; (c) granular oxidation; (d) adhering particles; (e) mechanical pits; and (f) solution pits; (**B**) SEM images and the corresponding EDS spectra of microplastics: microplastics fragments selected from (a) S1 and (b) S5.

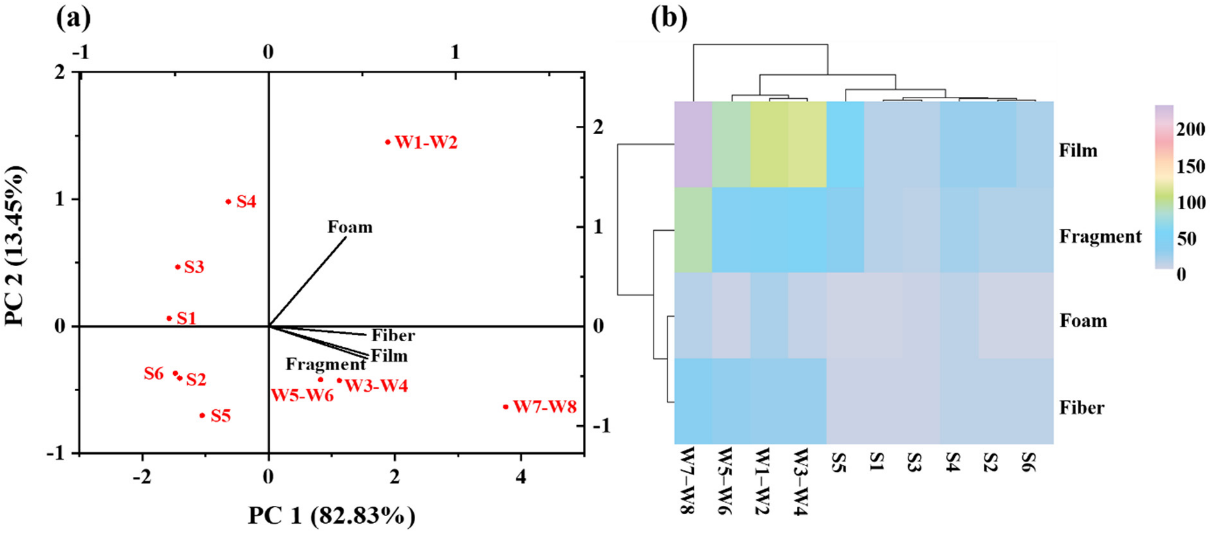

Figure 7. An analysis of microplastic species, using principal components (**a**) and a heat map (**b**) to cluster sampling sites in the Songshan Lake Basin, based on the shape distribution of the microplastics.

As shown in Figure 5, the Songshan Lake area contains a large number of film microplastics, mainly some white woven bags and transparent films, which may originate from terrestrial source input, the shattering, aging, and degradation of various packaging, bags, and plastic films used in daily life accumulated in the lake through rainwater runoff and other forms. Compared with the marine environment, the dynamics of the small lake system are weaker. So far, many microplastic studies have focused on the marine environment. Especially in urban lakes like Songshan Lake, there are no strong currents and very limited wave action to cause the physical decomposition of large plastic waste [26]. Therefore, photolysis and biodegradation are likely to be the main processes in the decomposition of large plastics [83]. By contrast, microplastic fragments usually come from industrial production and poorly managed plastic waste [84]. The fiber microplastics are mainly polypropylene, polyester and acrylic clothing fibers of various colors and some green polyethylene fishing net microplastics. A large number of fibers are present in laundry wastewater, and Browne et al. found that one garment can produce at least 1900 fiber microplastics by sampling household washing machines [85]. In addition, Cai et al. found that there were more fiber microplastics in the atmospheric environment based on the analysis of atmospheric deposition samples in Dongguan City [33]. Therefore, fiber microplastics may originate from the deposition of fibers in the atmosphere, washing of shore-side residential clothing, and stormwater runoff. Currently, we have very little information about how microplastics spread in terrestrial ecosystems [84], let alone how they get from land to water, and other sources typical of densely populated urban areas may be more likely to transfer them. The sources of microplastic contamination include construction materials, artificial turf, yard dust [86], and atmospheric deposition [87], as well as road runoff (vehicle-derived plastics, road coatings, deposition to pavement, roadside litter).

4. Conclusions

Microplastics were widely detected in the surface water bodies and sediments of Songshan Lake in Dongguan, indicating that this emergent pollutant is common in this area. The average abundances of microplastics in surface water and sediments of Songshan Lake were 2.29 ± 0.98 items/m^3 and 244 ± 121 items/kg. The compositions of common polymers found in the microplastics included PE, PP, PP–PE copolymer, PS, and PVC, with PE (47%) and PP (36%) being the most common. There were four microplastic shapes, including films, fragments, foams, and fibers, and the main shape in both the surface water and sediments was thin films, accounting for 60.7% and 49.2%, respectively. The most common sizes of the plastic particles in the surface water and surface sediments were in the ranges of 0.18–0.6 mm and 1–2 mm, respectively. The most common color of plastic particles in the surface water and sediments was transparent, accounting for 41% and 32% of microplastics, respectively. The concentration of microplastics was at a moderate level compared to sediments and surface waters of other freshwater systems. From the appearance of microplastics, the source of microplastics in the Songshan Lake area is mainly secondary sources. Moreover, positive correlations were observed among all four shapes of microplastics: films, fragments, foams, and fibers.

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