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Occurrence of microplastics in a pond-river-lake connection water system: How does the aquaculture process affect microplastics in natural water bodies

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ABSTRACT

Aquaculture activities have been considered to be important sources of microplastics to the water. Microplastic contamination closely related to aquaculture activities has been found in mariculture areas as well as in there nearby natural water bodies. However, for freshwater bodies with complex connectivity, it remains to be revealed how aquaculture activities affect microplastics in neighboring natural water bodies. In this study, we investigated the occurrence of microplastics of a water system consisting of aquaculture ponds, rivers, and lakes in June and December, which represented different aquaculture stages. The average microplastic abundances in June were 167 (67–367) items/m^3, 129 (67–233) items/m^3, and 372 (100–1167) items/m^3, respectively in the lake, river, and aquaculture ponds, while in December, those were 533 (200–933) items/m^3, 311 (200–600) items/m^3, and 429 (200–600) items/m^3, respectively. Microplastic abundance in ponds was significantly higher than in the river in June, while there was no significant spatial difference of microplastic abundance in December. Microplastics abundances in both river and lake were significantly higher in December than in June. The characteristics of morphology, size, color, and polymer type of microplastics were also different among different water bodies in June. However, the differences became smaller in December. The results of this study implied that the drainage of aquaculture ponds might increase the microplastics abundances of natural water in the water system predominated by aquaculture ponds. Further studies of the environmental fate of microplastics in ponds would be beneficial for understanding and controlling microplastics in the whole water system.

1. Introduction

Microplastic is an emerging contaminant with global concern in recent years. Plastic particles smaller than 5 mm have been found in different environments and the small size of microplastics and their ability to carry other pollutants make them susceptible to ingestion by aquatic organisms and cause toxic effects in terms of growth, reproduction, and inflammation, which makes their presence in the environment has received widespread attention (Ali et al., 2021). The hydrosphere is the most active field of microplastic research since it is the initial sphere of microplastic studies. Previous studies have revealed the occurrences of microplastics in oceans, rivers, lakes, and other special water bodies with concentrations ranged from lower than 1 items/m^3 to more than 10000 items/m^3 (Li et al., 2020; Liu et al., 2019; Waller et al., 2017). Microplastics in the hydrosphere are always involved in some large scale transport processes, including the transport from rivers to the ocean, the migration in the ocean with ocean currents, and the vertical migration from the surface layer to the deep sea (Katija et al., 2017; Lebreton et al., 2017; Petersen and Hubbart, 2021). As microplastic research expands to freshwater, it is necessary to study the fate of microplastics at a finer scale due to the various water types, complex connectivity patterns, and intense human activities in freshwater systems.

Freshwater system often exists as a complex network of interconnected water bodies of many sorts, such as rivers, lakes, ponds, wetlands, and reservoirs. The fate of biological and abiotic factors in these water systems are complex (Schmadel et al., 2019; Walks and Cyr, 2004; Zhang et al., 2011). Previous studies have revealed the fate of

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nutrients, organic pollutants, heavy metals, and antibiotics resistance genes (ARGs) in such freshwater systems (Luo et al., 2021; Mwanamoki et al., 2014; Tockner et al., 1999; Zhang et al., 2021c). However, a systematic understanding of the fate of microplastics in such water systems is still lacking.

Contaminants in the water were usually related to human activities. Aquaculture water system is a kind of water system prominently affected by human activities (Subasinghe et al., 2009), and almost all aquaculture activities are inseparable from the natural water bodies. Pond aquaculture is one type of aquaculture activity currently widely used and closely related to the surrounding natural water bodies (Belton and Azad, 2012; Ren et al., 2019). The area of pond aquaculture in China reaches almost the level of around 70% of the natural lake area (Yang et al., 2010). Previous studies have revealed high levels of pollutants in aquaculture ponds (Cai et al., 2013; Cheng et al., 2013, 2019; Xu et al., 2022). These pollutants are at risk of being released to natural water bodies (Cai et al., 2013; Wang et al., 2020). However, freshwater pond aquaculture is an important mode of freshwater aquaculture in China and globally and can provide a large amount of aquatic products for human consumption. A cleaner pond aquaculture pattern has an essential environmental significance. Investigating the fate of contaminants in freshwater systems dominated by aquaculture ponds is critical for determining the impact of ponds on related water systems. As an emerging contaminant received much concern in recent years and closely related to human activities, study of microplastics should naturally be a priority one in such water systems.

It has been demonstrated that there is a link between microplastics and aquaculture activities. Plastic ropes, nets, fences, boats, floats, cages, impermeable membranes, feeders, oxygenators, and packaging materials are all essential in the aquaculture industry (Lusher et al., 2017). Studies of coastal areas have linked high abundances of microplastics to marine culture activities (Feng et al., 2019; Kruger et al., 2020; Sun et al., 2020). Microplastic in some lakes are also considered to be related to aquaculture activities (Wang et al., 2018). Previous studies have reported the abundant of microplastics in aquaculture ponds which ranged from 3.52 items/m^3 to 875000 items/m^3 (Bordós et al., 2019; Ma et al., 2020; Zhang et al., 2021a). Xiong et al. (2021) has further identified different occurrences of microplastics in different types of aquaculture ponds. Microplastics in aquaculture ponds may penetrate and disperse throughout the water system as a result of water exchange between ponds and surrounding natural water bodies. However, there has been little investigation into this process. The middle and lower reaches of the Yangtze River in China contain a significant number of commercial aquaculture operations. (Wang et al., 2015). Understanding the fate of microplastics in these freshwater aquaculture systems is important for assessing the contribution of freshwater aquaculture to microplastic contamination in this watershed, which is recognized to be heavily affected by microplastics (Xiong et al., 2019). It also helps to reduce the generation of microplastics during aquaculture production by optimizing aquaculture patterns. In this study, we focused on a typical pond-river-lake connection water system in the middle and lower reaches of the Yangtze to reveal the spatial and temporal variation patterns of microplastics in different water bodies of this water system. In this way, we expanded the knowledge of the fate of microplastics in a complex freshwater system under human influence and determined the priority for minimizing microplastic contamination in similar water systems.

2. Materials and methods

2.1. Study area

This study was conducted in the lower Neijing River watershed around Honghu Lake, including Honghu Lake, Neijing River, and aquaculture ponds along Neijing River. This water system is located in Hubei province, which is a center of freshwater aquaculture in China (Wang et al., 2015). Honghu Lake is the seventh-largest natural lake in China, which is surrounded by aquaculture ponds. Previous studies revealed that there was a considerable abundance of microplastics in aquaculture ponds in this area (Xiong et al., 2021). Neijing River was an important tributary of the Yangtze River in Hubei Province, with a total length of 335 km. The middle and lower reaches of the river were gradually transformed into channels for the needs of plantation and aquaculture. Nevertheless, it still retained some features of natural river. The lower Neijing River watershed is an important pond aquaculture area. Aquaculture species include fish, crayfish, and crab. These ponds are connected to Neijing River through artificial ditches, which draw water from and drain water to Neijing River. The study area features a typical subtropical monsoon climate with four distinct seasons, hot and rainy in summer, and cold and dry in winter.

2.2. Sampling

A total of twenty-eight sampling sites were collected in the study area, including seven sites in Honghu Lake, seven sites in Neijing river, and fourteen aquaculture ponds near the river sites (Fig. 1). These ponds included different types of crayfish, mitten crab and fish ponds, ranging in surface area from 0.5 to 4 ha, with water depths between approximately 1-2 m. The details of the pond are described in the supplementary material. Sampling events were performed in June and December 2020, corresponding to the summer wet period and winter dry period of the study area, respectively. They are also the middle and final stages of the pond aquaculture process, representing the different states of pond aquaculture water storage and drainage, respectively. Some of the sample sites were not available for microplastics sampling due to the fact that the sites had dried up (Table S1). In this study, microplastic was sampled as the method performed by Xiong et al. (2021). Depending on the turbidity of water in the field, fifteen to 60 L of water sample were collected with a pre-washed stainless-steel bucket and filtered through a pre-washed stainless-steel sieve with 25 μm pore size at each sampling site. The residues on the sieve were rinsed into a pre-washed glass jar using deionized water (DI water) and covered with a glass lid. The water samples were stored in a cooler and transferred to the laboratory for the further analysis. Water sample for the determination of physical and chemical parameters was also collected at each site and the water temperature (WT), dissolved oxygen (DO), pH, and turbidity were measured in situ using a YSI (Yellow Springs, Ohio, United States) Pro 20 portable multiparameter water quality analyzer.

2.3. Sample preparation

Water samples were also prepared according to the method described by Xiong et al. (2021) with slight modifications. After drying at 60 °C, water samples were digested with 30% hydrogen peroxide at 60 °C for 72 h to remove the organic matters. The digested samples were then density separated with saturated sodium chloride solution (1.2 g/cm^3), which was pre-filtered through GF/C filter (1.2 μm pore size), in separating funnels. After precipitation for 24 h, particles floating on the surface were filtered onto filters (1.2 μm pore size, Millipore S-Pak). All filters were stored in clean petri dishes and then air-dried for further examination.

2.4. Sample analysis

Microplastics on the filter were observed with a stereomicroscope (Olympus SZ61, Japan). The quantity, shape, size, and color of suspect microplastics were recorded. The microplastics in this study were divided into two morphological categories as fragment and fiber, and two categories of particle size as large and small by the boundary of 500 mm. Although it can be further classified into a variety of shapes, a unified classification of the various shapes into fibrous and fragmented microplastics can better represent the distinctions in microplastic

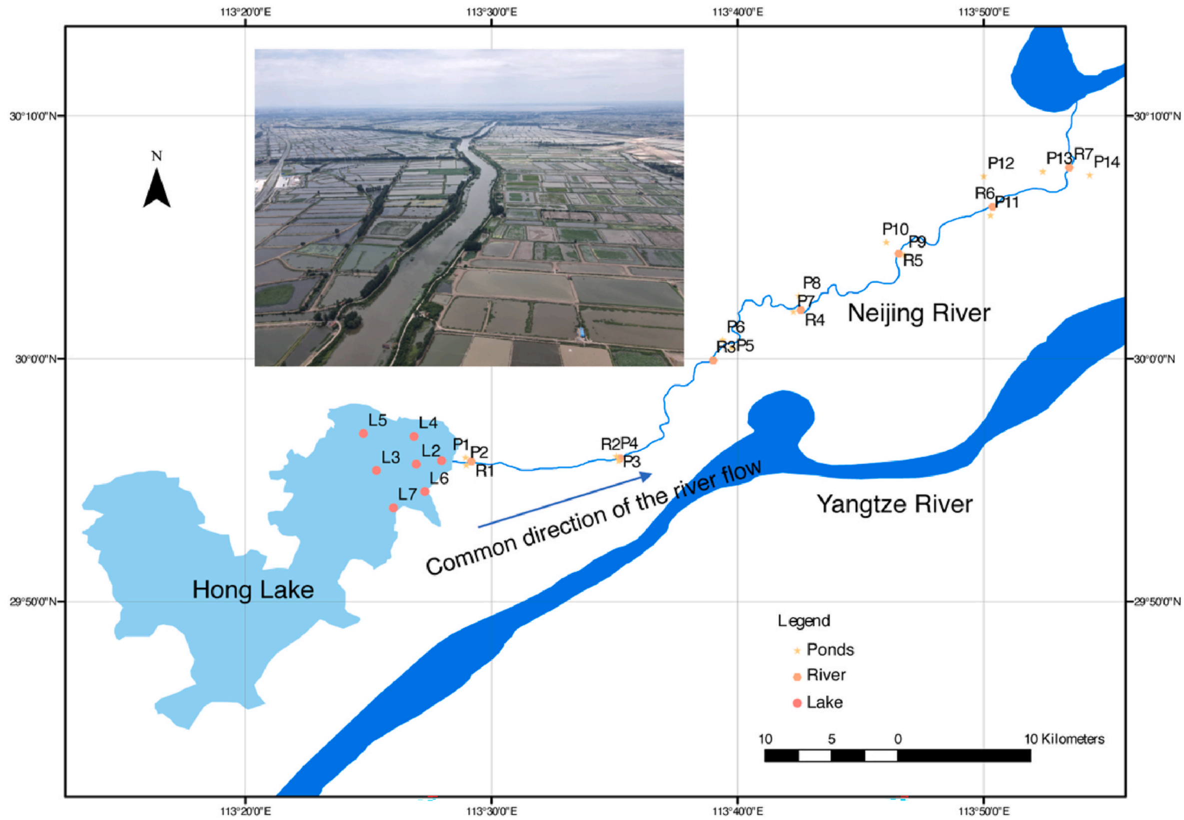

Fig. 1. Study area and sampling site of this study.

sources. Fibrous microplastics mainly come from fabrics (Cai et al., 2020), while fragmented microplastics (containing sheets, fragments, films, lines, foams, etc.) mainly come from the fragmentation of plastic waste (Xiong et al., 2018; Zhang et al., 2018). After visual observation, the filter of each site was analyzed by a Renishaw inVia Raman microscope (Wotton-under-Edge, Gloucester-shire, UK) to identify if the suspect microplastics were synthetic polymer and what types of polymers they were. The wavelength of the laser was 785 nm with a Raman frequency shift of 300–3200 cm. Instead of referring to the similarity on the software, we determined the broad types of polymers directly by comparing the characteristic peaks of the Raman spectrums. The Raman spectrums of the particles were compared with the software's own library of spectrums and the spectrums of self-made standard plastic samples.

Total phosphorus (TP), total nitrogen (TN), soluble reactive phosphorus (SRP), nitrate, nitrite, and ammonia of water samples were measured in the laboratory according to the Chinese national standard method (SEPA, 2002). Total organic carbon (TOC) was analyzed using Elementar vario TOC select (Langenselbold, Germany).

2.5. Quality assurance and quality control

To prevent contamination, the entire sampling and experimental process avoided the use of plastic products as much as possible. Sampling and experimental tools were rinsed thoroughly with pure water before use. During analysis, all exposed wares were covered or wrapped with aluminum foil. The solutions used in the experiments were filtered through 1.2 μm GF/C glass filters. Cotton jackets or lab coats were worn throughout the experiments and sampling. Blank controls were set up throughout the experiment, and microplastics similar to those in the blank controls were subtracted from the final calculation of results.

2.6. Data analysis

The abundances of microplastics were expressed by items/m^3 in the water. Mann-Whitney U and Kruskal-Wallis 1-way ANOVA test were used to identify the temporal and spatial differences of microplastic abundances (significance level of 0.05). Principal component analysis (PCA) was used to find the relationship between microplastic abundance and other water parameters. Microsoft Excel 16.52, R 4.0.3, and ArcGIS 10.2 were used for plotting.

3. Results and discussion

3.1. Spatial and temporal variation of microplastic abundance in the water system

In the present study, the abundance of microplastics in June were range from 67 to 367 items/m^3, 67 to 233 items/m^3, and 100–1167 items/m^3, respectively in the lake, the river, and aquaculture ponds, while in December, those were range from 200 to 933 items/m^3, 200 to 600 items/m^3, and 200 to 600 items/m^3, respectively (Fig. 2a and b). In June, the average abundance of microplastics was highest in aquaculture ponds (372 items/m^3), followed by the lake (167 items/m^3), and the river (129 items/m^3), the average abundance of microplastics was significantly higher ($p < 0.05$) in ponds than in the river. Whereas, in December, there were no significant differences among ponds (429 items/m^3), the river (311 items/m^3), and the lake (533 items/m^3). For temporal comparison, the abundance of microplastics in the lake and the river were all significantly higher ($p < 0.05$ for the lake and $p < 0.01$ for the river) in December than in June (Fig. 2c). However, there was no significant difference in the abundance of microplastics in the ponds between the two surveys. The differences in microplastic abundance between pond sample sites were greater in June. Although the highest values of microplastic abundances in the ponds were found in June at P8

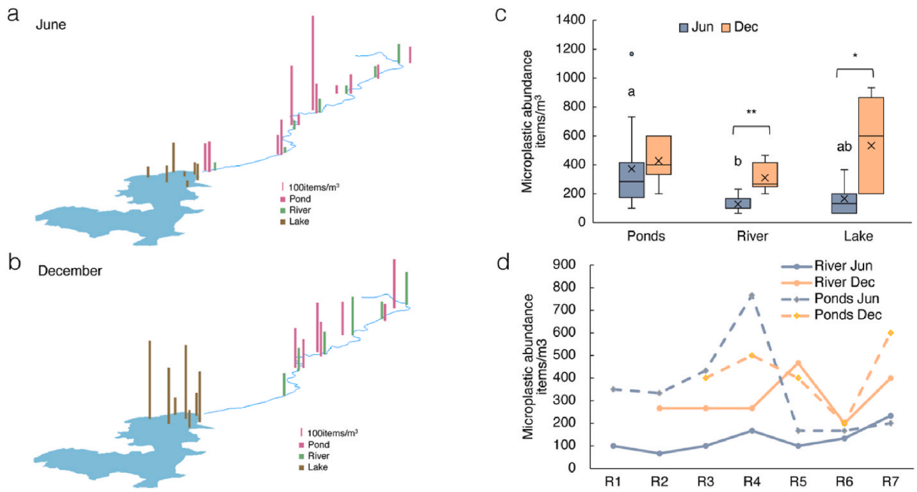

Fig. 2. Spatial distribution of microplastics in different kinds of water bodies in the pond aquaculture dominated water system, a) in June and b) in December; c) Comparison of spatial and temporal variations of microplastic abundances of different types of waterbodies in the water system. "a" and "b" indicate whether there is a significant difference ($p < 0.05$) between different types of water bodies; "*" ($p < 0.05$) and "**" ($p < 0.01$) indicate significant differences between months; d) Variation of microplastic abundance from upstream to downstream at sample sites in the Neijing River and surrounding ponds. The horizontal coordinates indicate the river sample points, while the pond data in the plot are the average microplastic abundances of the pond sample points adjacent to the river sample points.

(1167 items/m^3) and P6 (733 items/m^3), the lower values were also found in June (about 60–100 items/m^3).

The abundance of microplastics in this study was similar to the previous study of different types of aquaculture ponds in the watershed of Honghu Lake (Xiong et al., 2021). Compared to microplastic abundance in some heavy polluted areas such as fish ponds in the Pearl River Estuary (10300–87500 items/m^3), Wuliangsuhai Lake (31200–112500 items/m^3), and Taihu Lake (3400–25800 items/m^3), the abundance of microplastics in this study was essentially lower (Ma et al., 2020; Mao et al., 2020; Su et al., 2016). Aquaculture has been proven to be a significant source of microplastics by several studies, but the microplastic abundances in these studies ranged widely from 3.52 items/m^3 to 875000 items/m^3 (Bordós et al., 2019; Feng et al., 2019; Ma et al., 2020; Zhang et al., 2021a). The results of our study are moderate among these aquaculture ponds studies. As an important pond aquaculture-dominated water system, the water bodies in this study were inevitably subject to microplastics from pond aquaculture activities. On the other hand, previous studies indicated that the high values of microplastic abundances in the middle and lower reaches of the Yangtze River were closely related to the distribution of metropolitan cities (Xiong et al., 2019). However, the area of this study was far from the major cities. Meanwhile, the abundant water in the area and the relatively frequent water exchange process required by the pond aquaculture activity might dilute the abundance of microplastics and influence microplastics enrichment in single water body, which led the abundance of microplastics in the water system at a moderate level.

The pond aquaculture influenced the spatial and temporal distribution of microplastics in this water system. Aquaculture ponds might be the most significant sink for microplastics in the water system during the aquaculture process before drainage. Plastic waste used in the aquaculture and other human activities could be discharged into the aquaculture ponds and broke down to microplastics (Ma et al., 2020; Xiong et al., 2021; Zhang et al., 2021a). The abundance of microplastics in ponds was significantly higher in June compared to the river, whose water is more exchangeable. When microplastics in other water bodies within the water system were reduced by natural flow or dilution via precipitation in June, the abundance of microplastics inside the aquaculture pond stood out because of its confinement. While In December, the microplastics accumulated in the ponds might be dispersed to the whole water system due to the regular drainage after an aquaculture period (Ling and Weimin, 2010). It resulted in microplastic distribution characteristics that did not differ significantly among water bodies throughout the water system in December and significantly higher microplastic abundance in the lake and river when compared to June. Previous studies have revealed that other culture-related pollutants also exhibit diffusion from aquaculture ponds to nearby natural water bodies (Cai et al., 2013; Wang et al., 2020). From the perspective of microplastic abundance, this study provided additional evidence that the distribution of aquaculture-related contaminants in water systems predominated by aquaculture ponds might be driven by aquaculture processes.

Precipitation runoff was thought to transport land-derived microplastics in the watershed to water bodies (Xia et al., 2020). Jianghan Plain region is under the influence of monsoon climate, which makes June the beginning of the wet season (Yu et al., 2018). Our sampling year was also one of the very prominent wet years in the middle and lower reaches of the Yangtze River (Wei et al., 2020). Some highest abundances of microplastics found in some pond sites in June might be related to the contribution of precipitation runoff. However, higher abundances of microplastics in December than those in June in the whole water system in this study indicated that the dilution effect due to heavy precipitation might be greater than the input of plastic waste from surface runoff during the wet season in this study. The area of aquaculture ponds around Honghu Lake is very large. However, the watershed area of individual pond is small. The pond clusters may reduce the watershed area of natural water bodies and further reduce their plastic wastes input. Most of the land-derived plastic waste carried by surface runoff might first enter a single pond sub-watershed and then be transported to natural water bodies through drainage. Summer is rarely the season when ponds need frequent water exchange and only need drainage when facing heavy precipitation. It also implied that the microplastics in the ponds, which were not high in abundance in June, were only out of the pond after being diluted by precipitation. Moreover, plastic wastes also needed time to break down to microplastics after transported into the ponds (Julienne et al., 2019; Xiong et al., 2021). It might be the reason for the low abundance of microplastics throughout the water system in June.

Rivers took on the job of transport microplastics, as other aquaculture contaminants (Xu et al., 2022), from ponds to natural water bodies. Although the section of Neijing River investigated in this studied did not always flow into Honghu Lake, the study area could still be indicative of the area, where rivers terminated in the lake. Comparing microplastic abundances at Neijing River sites and the adjacent pond sites, it could be found that the spatial trends of microplastic abundance at the river and pond sample sites exhibited a similarity in both June and December (Fig. 2d). The abundance of microplastics in the river and ponds reached peaks at the similar area. It further indicated the impact of microplastics from ponds on the river through aquaculture process. Previous studies suggested that microplastic abundance was significantly higher in crayfish and crab ponds than in fish ponds in the Honghu Lake watershed (Xiong et al., 2021). However, in this study, the abundance of microplastics in the lower Neijing River aquaculture pond area, where the fish pond was dominant, was not lower than that in the upper Neijing River area, where crayfish and crab ponds were dominant. It might be due to the longer period of fish culture in some fish ponds than the annual crayfish and crab culture period, while the longer retention time favored the generation of more microplastics (Julienne et al., 2019). In addition, differences in human activities in different regions may also influence the contribution of June precipitation to microplastics in different ponds.

There was a spatial lag in the peak of microplastics in the river in December compared to the pond, while in June it presented a high spatial consistency (Fig. 2d). As discussed above, due to the absence of the drainage process, ponds provided less materials to the water system in June. Microplastic abundances in both aquaculture ponds and rivers might be more consistent in reflecting regional input processes of terrestrial sources microplastics. For example, the area near site R4, which exhibited the highest abundance of microplastics in June, might have been influenced by microplastics from one of the large towns along Neijing River. In contrast, in December, the drainage dominated the change of microplastic abundance within the water system. It might result in spatial lag in river microplastic abundance relative to the ponds at some sites due to differences in the location of the ditches connecting the aquaculture ponds to Neijing River.

3.2. Differences in microplastic characteristics of water bodies within the water system

Microplastics in most of the sample sites in this study were predominated by fibrous microplastics (Fig. 3a and b), which was consistent with the results of some previous studies (Jiang et al., 2019; Su et al., 2016; Xiong et al., 2021). However, some sites, especially those in the ponds and river in June, exhibited a predominance of fragments. While in December, the predominance of fragments in the ponds and river was decreasing and a higher proportion of fragments appeared in the lake (Fig. 3a and b). Since fragmented microplastics usually came from the weathering of plastic waste (Zhang et al., 2021b), it suggested that ponds and the river were hosting more plastic waste generated by human activities in the watershed, especially in the middle stage of aquaculture. As mentioned above, the presence of the pond clusters compressed the watershed area that directly entered the lake, which not only affected the abundance, but also affected the morphological of microplastics in the lake during the aquaculture process. The proportion of fibrous microplastics was also high in some regions with less impact from human activities (Bergmann et al., 2019; Dong et al., 2021; Jiang et al., 2019). It might also indicate that the lake was less affected by aquaculture activities in June, but more affected by aquaculture activities after the drainage in December.

Microplastics smaller than 500 μm were predominated in most sites

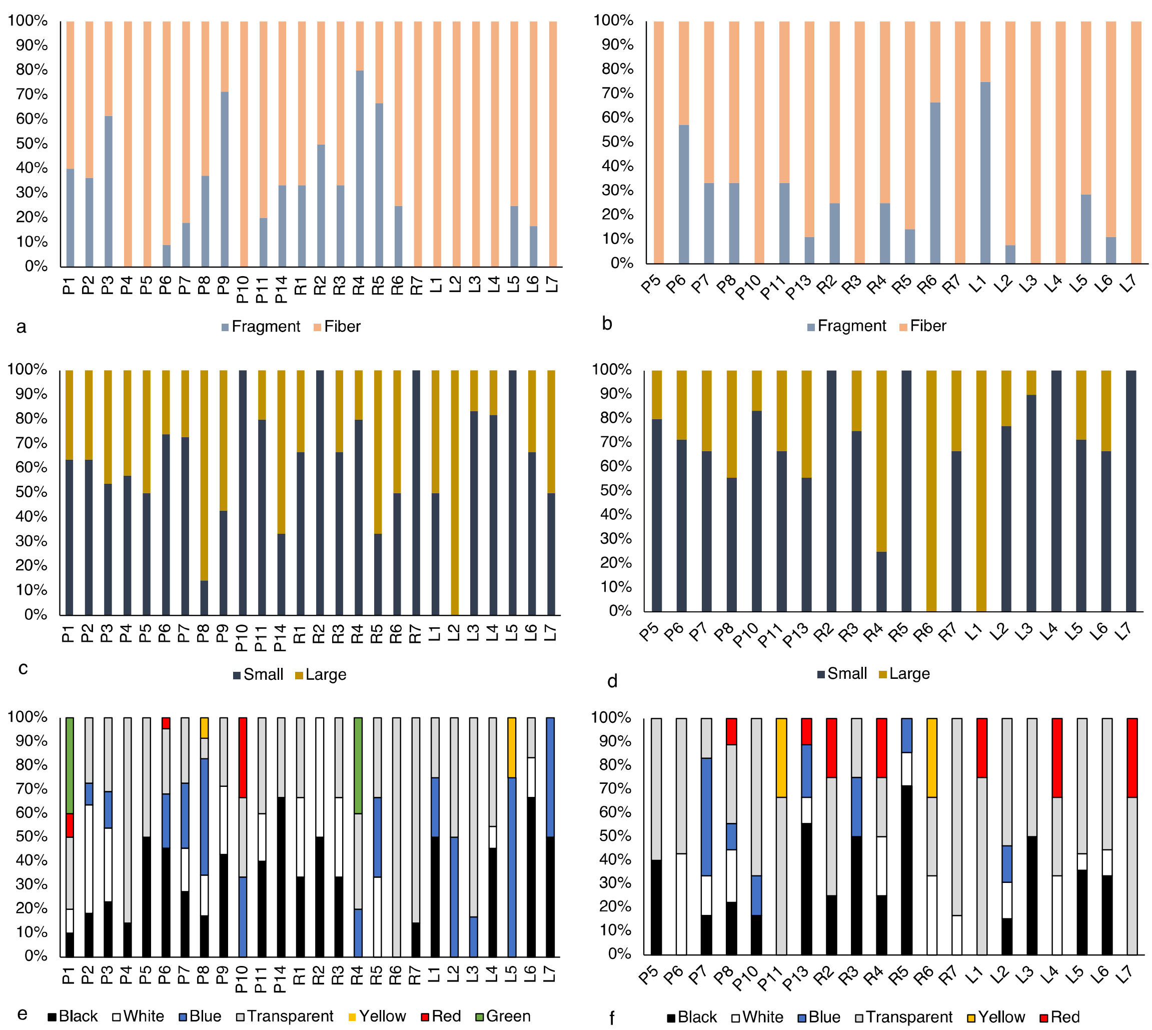

Fig. 3. Morphological characteristics of microplastics in different sites in the water system in June (a) and December (b); Size characteristics of microplastics in different sites in the water system in June (c) and December (d); Colors of microplastics in different sites in the water system in June (e) and December (f).

in this study. Relatively higher proportions of large microplastics were found in pond sites in June compared to December. However, there were no such trends in the river and the lake (Fig. 3c and d). Previous studies suggested that the predominance of small size microplastics was an essential feature of microplastic in some natural water bodies (Jiang et al., 2019; Mao et al., 2020; Wang et al., 2018). The generation of microplastics in the natural environment is generally a process of gradual breakdown from large plastics to microplastics, which also means that it takes some time to convert from plastic waste to microplastics (Julienne et al., 2019). June was in the pre-middle stage of pond aquaculture, and the plastic waste that entered ponds during the single aquaculture period might not have enough time to break down to smaller microplastics, while in December at the end of the aquaculture process, microplastics in ponds gradually became smaller over time. In addition, the consistency of microplastic particle size distribution in the whole water system in December further suggested that the pond aquaculture system could have an important influence on the microplastic characteristics within the water system.

Although more colors of microplastics were found in the whole water system in June (7 colors) than in December (6 colors), the diverse colors were mainly concentrated in ponds and colors of the river and lake sites were mainly concentrated in four colors: black, white, transparent, and blue, which were common in the environment (Rezania et al., 2018). Whereas, in December, although the proportions of blue microplastics became less, the frequency and proportion of both red and yellow microplastics increased in both river and lake sites (Fig. 3e and f). Diverse of microplastic colors might reflect microplastics affected by various plastic wastes sources (Wang et al., 2018), although a direct link between sources and colors had not been established yet. The results of this study suggested that microplastics from complex sources within the watershed mainly entered ponds in June, while in December, they affected the river and lake from ponds. It further supported our hypothesis that aquaculture ponds could affect microplastics in the whole water system through the drainage.

In this study, five types of polymers including polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS), and polyamide (PA) were identified in the June, while four polymers including PE, PP, PET, and polyvinyl chloride (PVC) were identified in December (Fig. 4 and Fig. S1). In June, the proportions of PE, PP and PET were closer overall, while the other two polymer types were only found sporadically in the lake. Whereas in December, PET was significantly dominant in both ponds and the lake, followed by PP, but in the river, the proportion of predominant polymer types was not different from that in June. PE, PP and PET are the most common types of polymers in the environment and are the most used types of plastics at present (Andrady, 2017). PE and PP microplastics are mainly derived from the decomposition of plastic waste and can also be found in fibers (Efimova et al., 2018; Xiong et al., 2021), while PET fibers are mainly derived from the fibers of fabrics in the environment (Dalla Fontana et al., 2020). The polymer types of microplastics in this water system were similar to other studies, and still predominated by several common polymer types currently available. The plastic products involved in aquaculture were mainly made of common commercial plastic materials including PE and PP (Lusher et al., 2017), while the input of PET fibers might originate from ubiquitous fiber sources including atmospheric transport, laundering, and clothing abrasion (Cai et al., 2020; Zhang et al., 2020). From the seasonal changes in polymer types, combined with the morphological changes of increasing fibrous, it could be assumed that the source of microplastics for ponds were dominated by fabric fiber throughout the aquaculture period, while in the wet season, land-derived plastic waste still made a critical contribution to microplastics in water system.

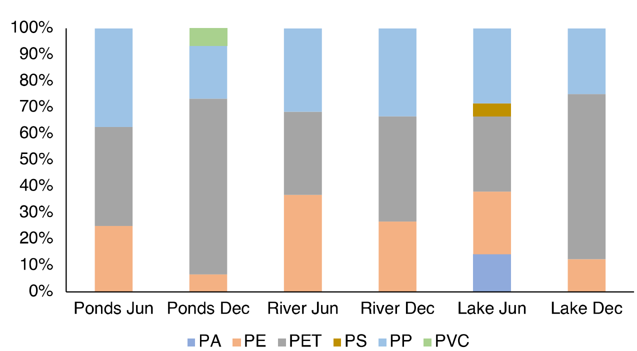

Fig. 4. Polymer types of microplastics in different water bodies in the water system in different seasons.

The spatial and temporal differences in microplastic characteristics of different water bodies further indicated the influence of pond aquaculture on the occurrence of microplastics in this water system. Extensive aquaculture ponds in the watershed could become critical sinks of microplastics during the aquaculture process, leaving plastic pollution from human activities in the watershed within the aquaculture ponds (Ma et al., 2020; Zhang et al., 2021a; Xiong et al., 2021). It also made the microplastic characteristics of aquaculture ponds different from surrounding natural water bodies, especially lakes that are not directly connected, in the mid-culture period (Xiong et al., 2021). After the aquaculture period, the drainage converged the microplastic characteristics of all water bodies in the water system, which further indicated that the aquaculture ponds became an important source of microplastics for natural water bodies in the water system. Moreover, since the annual water exchange process was relatively frequent (Ling and Weimin, 2010), the microplastic characteristics of the natural water bodies within the whole water system might eventually be similar to the microplastic characteristics of aquaculture ponds at the end of the aquaculture period. Therefore, the results of this study indicated that further research on the fate of microplastics in aquaculture ponds during an aquaculture period was critical for identifying the characteristics of microplastic throughout all water bodies in the aquaculture area.

3.3. Relationships between microplastic and environment indicators in the water system

Microplastic abundance in June was a significant contributor to the principal component with DO, pH, nitrite, and nitrate, which exhibited positive correlations with DO and pH and negative correlations with nitrate and nitrite (Fig. 5a). In December, microplastic abundance remained in the principal component with similar water parameters, but the contribution was lower than in June (Fig. 5b). Due to the heavy inputs during the aquaculture process, nitrogen and phosphorus nutrients have been considered as critical aquaculture pollutants that affect the water environment of surrounding natural water bodies (Herath and Satoh, 2015). The nitrogen and phosphorus from pond aquaculture entered surrounding natural water bodies through the wastewater of aquaculture (Ling and Weimin, 2010), which was similar to the pathway of microplastics into natural water bodies inferred above. However, from the results of PCA, the abundance of microplastics in different water bodies within the whole pond aquaculture water system did not exhibit a strong correlation with nitrogen and phosphorus. It might be due to the differences in the environmental behavior of microplastics in the water system compared to nitrogen and phosphorus.

Nitrogen and phosphorus in the water could transformed or deposited through microbially driven geochemical processes or adsorption (Galloway et al., 2008; Wang and Li, 2010), while the fate of microplastics in the water column was mainly driven by the density of the material, the attachment of biofilm and particulate matter which might affect the density, and the ingestion by aquatic organisms (Chen et al., 2019; Katija et al., 2017; Rummel et al., 2017). The different influencing factors might lead to the absence of a close relationship between microplastics and nutrients in the water of pond aquaculture water

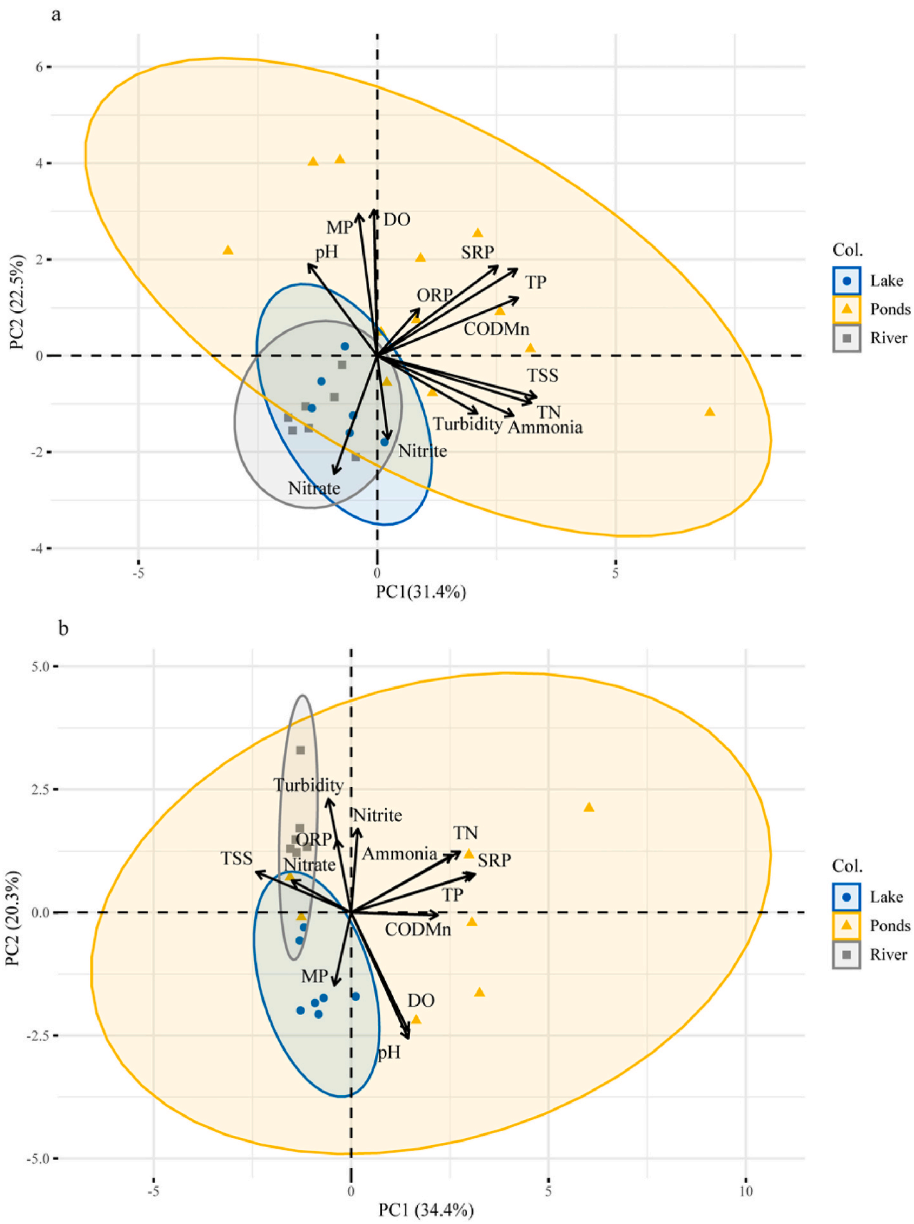

Fig. 5. PCA results for microplastic abundance and environmental indicators within pond aquaculture water systems for June (a) and December (b).

system. The water bodies within the aquaculture water system were in a eutrophic state due to the long-term influence of aquaculture activities, which could easily lead to lower DO levels (Ling and Weimin, 2010) and aquaculture ponds commonly improved DO through aeration and other measures (Rogers, 1989). The aquaculture activities might also interfere with the pH of the water column. The correlation between microplastic abundance and DO and pH in the water system, especially in June, might also reflect the effect of aquaculture activities on microplastic abundance.

4. Conclusions

The results of this study indicated that in a pond aquaculture dominated water system, pond aquaculture activities could significantly affect both the abundance and characteristics of microplastics in natural water bodies. During the aquaculture period, the aquaculture ponds received the major inland-sourced plastic wastes in the water system, and the microplastics they received through an entire aquaculture period were in turn transported into the surrounding natural water bodies via the drainage process at the end of the aquaculture period. Natural or man-made rivers and canals connected to the aquaculture ponds became the conduits for transporting microplastics during the drainage period, while the lake in the water system eventually became the sink of microplastics after drainage. Due to the great influence of aquaculture ponds and the frequent exchange between water bodies in the water system, the microplastic characteristics throughout the water body tended to be the same as in the aquaculture ponds at the end of the aquaculture period. There was no significant correlation between microplastic abundance and nutrient indicators within the water system due to differences in environmental fate. Due to the impact of pond culture on microplastic contamination of natural water bodies within the water system in which it is located, it is necessary to control the use of plastic products during pond aquaculture processes and to properly dispose of the plastic waste generated in order to achieve cleaner aquaculture production. The results of this study suggested that further research on the sources, environmental behavior, and control measures of microplastics in aquaculture ponds, especially on the accumulation of microplastics in sediments and aquatic organisms in ponds aquaculture water systems, would be important for controlling microplastic in artificial and natural water bodies within the whole water system dominated by aquaculture ponds.

CRediT authorship contribution statement

Xiong Xiong: Writing – original draft, Methodology, Visualization, Writing – review & editing. **Shenghao Xie:** Methodology, Visualization. **Kai Feng:** Investigation. **Qidong Wang:** Supervision, Conceptualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.131632.

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