Microplastics in Taihu Lake, China*

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A B S T R A C T

In comparison with marine environments, the occurrence of microplastics in freshwater environments is less understood. In the present study, we investigated microplastic pollution levels during 2015 in Taihu Lake, the third largest Chinese lake located in one of the most developed areas of China. The abundance of microplastics reached 0.01 \times 10^{–6}–6.8 \times 10^{10} items/km² in plankton net samples, 3.4–25.8 items/L in surface water, 11.0–234.6 items/kg dw in sediments and 0.2–12.5 items/g ww in Asian clams (Corbicula fluminea). The average abundance of microplastics was the highest in plankton net samples from the southeast area of the lake and in the sediments from the northwest area of the lake. The northwest area of the lake was the most heavily contaminated area of the lake, as indicated by chlorophyll-a and total phosphorus. The microplastics were dominated by fiber, 100–1000 \mu m in size and cellophane in composition. To our best knowledge, the microplastic levels measured in plankton net samples collected from Taihu Lake were the highest found in freshwater lakes worldwide. The ratio of the microplastics in clams to each sediment sample ranged from 38 to 3810 and was negatively correlated to the microplastic level in sediments. In brief, our results strongly suggest that high levels of microplastics occurred not only in water but also in organisms in Taihu Lake.

1. Introduction

Widespread use of synthetic polymers, so-called plastic, has changed our ways of life. However, the huge production of plastic has resulted in serious environmental concerns (Cózar et al., 2014; Rocha-Santos and Duarte, 2015). In particular, the small-sized plastic particles that originate from manufacturing (primary sources) and the degradation of large items (secondary sources) are prone to accumulate in the environment and may pose an unpredictable influence on the ecosystem (Cole et al., 2011; Wright et al., 2013). The small particles (< 5 mm) are defined as microplastic (Thompson et al., 2004). Concerns about microplastic and its associated environmental issues have arisen worldwide (Barboza and Gimenez, 2015).

Because of their ubiquitous presence and morphological features, microplastics are likely to threaten the life and development of biota via direct and indirect pathways, including contact, uptake and digestion (Farrell and Nelson, 2013; Desforges et al., 2015; Long et al., 2015). Microplastics provide substratum sorption of various persistent organic pollutants (POPs). Microplastics may pose a potential risk to the ambient environment because of their tendency to release certain contaminants (Bakir et al., 2014; Napper et al., 2015). Microplastics also have potential risks for human health because of their ability to persist through the food chain (Brennecke et al., 2015). Therefore, it is very important to understand the fate and behavior of microplastics in the environment.

To date, microplastics have been well documented in marine environments worldwide (Thompson et al., 2004; Cózar et al., 2014; Law and Thompson, 2014). Microplastics have even been found in abiotic sea products such as sea salts (Yang et al., 2015). However, the occurrence of microplastics in freshwater environments is less understood (Driedger et al., 2015; Eerkes-Medrano et al., 2015). Freshwater systems have several important functions, such as the use as providing sources of drinking water and fisheries. Some freshwater systems are surrounded by a high population density, and such intensive anthropogenic activity can introduce various contaminants, including microplastics, into the
body of water (Floehr et al., 2013; Ismail et al., 2014; Driedger et al., 2015). In recent years, the occurrence of microplastics has been documented in several lakes and rivers (Eriksen et al., 2013; Castaneda et al., 2014; Yonkos et al., 2014). To date, however, field studies have only reported microplastic burden in limited freshwater organisms (Faure et al., 2015; Peters and Bratton, 2016).

Taihu Lake is the third largest freshwater lake in China. It is located in one of the most developed areas of China, the Yangtze River Delta. Taihu Lake is also well known for its fisheries and tourism. However, with the development of the local economy and industry, Taihu Lake has become one of the most severely polluted lakes in China (Liu et al., 2009; Yan et al., 2014). In the present study, we investigated microplastic pollution levels in water, sediments and an organism of Taihu Lake. Our purpose is to determine the extent of microplastic pollution in a lake located in an area with intensive anthropogenic activities. We found high levels of microplastic pollution in Taihu Lake and propose that the Asian clam (Corbicula fluminea) could be used in the biomonitoring of microplastic pollution in this freshwater system.

2. Material and method

2.1. Research area and sampling sites

Taihu Lake has a surface area of approximately 2000 km² and a mean depth of 1.9 m (Hu et al., 2006). Three rivers (Yincungang River, Wujingang River and Zhihugang River) are connected to the northern bay of Taihu Lake and account for 1/3 of the total inflow to Taihu Lake (Fig. 1). The Taipu River is connected to the southern region of Taihu Lake and accounts for 2/3 of the total outflow from Taihu Lake. There are three waste water treatment plants that have a treatment capacity of larger than $5 \times 10^4$ m³/day. Taihu Lake represents a critical drinking water source for local population of approximately 20 million people. The industry and agriculture in the Taihu Basin provide 14% of China’s gross domestic product (Wang et al., 2015). Therefore, Taihu Lake plays an important role in the regional economy and social development.

In August 2015, samples were collected from 11 locations, which were chosen for prospective pollution level and geographic region (Fig. 1). These sites represent three different areas of Taihu Lake. Sites 1—4 were located at the northwest area of the lake and close to cities and rural areas. These sites were believed to be affected by intense levels of anthropogenic activity. Sites 5—8 were located in the central area of the lake. Sites 9—11 were located in the southeast area of the lake, where there is less anthropogenic pollution coming from the surrounding land. Two other farmed sites (F1-2) were added to the sample collection in November 2015.

2.2. Sample collection

In August 2015, water, sediment and organism samples were collected. The dissolved oxygen (DO), pH, chlorophyll-a (Chl-a) and ammonia nitrogen (NH₄⁺) were also measured in situ using a multi-parameter probe system. One liter of surface water was sampled at each site and sealed in glass bottles for further analysis of total phosphorus (TP) and total nitrogen (TN). The wind condition was measured using a Kestrel 4500 shooter’s weather meter.

Prior to sampling, all sampling containers and tools were...
washed using filtered tap water (0.45 μm) and sealed. A cotton coat and nitrile gloves were worn at all time during sampling. A total of 11 floating microplastic samples were collected using a nylon plankton net with a circular opening (0.65 m in diameter, 1.55 m in length and 333 μm in mesh size). Three individual tows were fixed at the opening of the net and towed by the side of boat at a speed of 2 km/h for 1–30 min. Half of the net was deliberately kept under water during towing, and the floating microplastics from the surface water layer (less than 0.3 m deep) were collected. The towing distances used for each sample varied with the degree of algae blooming at each site. With the exception of S7 (towing distance of 1700 m) and S8 (towing distance of 2500 m), the towing distances ranged from 25 to 125 m due to the large algae blooms present. Approximately 250 mL of sample was collected and immediately preserved with 5% methanoldehyde in a 1-L glass bottle. The bulk surface water was collected three times using a steel sampler at each site. The water was then pooled, and 5 L of bulk water was kept as one sample for each site. Similarly, the sediments were collected three times using a Peterson sampler and pooled. Approximately 2 kg of the pooled sediments were kept in an aluminum foil bag as one sample from each site.

A bottom fauna trawl was used to collect clams. All of the sediments were pooled into a steel mesh with pore size of 1 mm and washed in situ using lake water. The clams were picked up and kept in an aluminum foil bag. Clams were collected from sites S3–11, with 3–20 individual specimens collected from each site in August. An additional survey for microplastics in clams was conducted in November. Clams were collected from all 11 sites as well as two farmed sites (F1 and F2), with 5–50 individual specimens collected from each site. The water and sediment samples were kept at 4 °C, and the clams were kept at –20 °C in the laboratory for further analysis.

2.3. Isolation of microplastics

A series of efforts were made to avoid airborne contamination in the laboratory. The liquid used in all of the experiments was filtered with a 0.45-μm filter prior to use, and all of the equipment was rinsed three times with filtered tap water. The samples were immediately covered by aluminum foil if they were not in use. Blank groups were analyzed simultaneously to estimate the background contamination. Samples from the plankton net and surface water were filtered through a 47-mm-diameter filter (Millipore TMTM polycarbonate filter). The filter pore size was 100 μm for plankton net samples and 5 μm for surface water samples. The substances collected on the filters were immediately washed into glass bottles using hydrogen peroxide to digest any organic matter (30%, V/V). The glass bottles were covered and placed in an oscillating incubator at 65 °C and 80 rpm for approximately 72 h. The liquid in the bottles was filtered again, and these filters were stored dry for further observation. It was necessary to filter the samples twice to remove the organic matter in these biota-rich samples due to the eutrophication.

The microplastics were isolated from sediments was done using the method of Klein et al. (2015) with modification. Briefly, 1 kg of wet sediment was mixed with a saturated sodium chloride solution (360 g/L) using a ratio of 1:2 (V/V) in a 10-L glass container with a depth of 40 cm. The mixture was stirred for 30 min and allowed to settle overnight. The supernatant, including any floating particle, was transferred onto a 47-mm-diameter filter with a 5-μm pore size. The hydrogen peroxide treatment and the isolation of microplastics was then performed as with the plankton sample processing method above.

The isolation of microplastics from organisms was carried out according to the method of Li et al. (2015a). Briefly, the shell length and weight of each individual clam were recorded. The soft tissue of the clam was separated and weighted (Supplementary materials Table 1). For the samples collected in August, the soft tissue of the clams from a sampling site was pooled into a single sample. For the samples collected in November, the soft tissues from 1 to 5 clams was used as a replicate. Approximately 200 mL of hydrogen peroxide was added to each bottle, and the isolation of microplastics was performed as with the plankton sample processing method above.

2.4. Observation of microplastic

The filters were observed under a Carl Zeiss Discovery V8 Stereo microscope (Microimaging GmbH, Gottingen, Germany), and all images were taken with an AxioCam digital camera. Visual assessments were applied first to quantify the suspected microplastics according to the physical characteristics of the particles. In all, 1805 particles were visually identified. A subset of 113 particles were then selected and verified using micro-fouier transformed infrared spectroscopy (μ-FT-IR) or scanning electron microscopy/energy dispersive spectroscopy (SEM/EDS). The selected particles represented the most common types of visually identified particles and were selected from all of the filters. The final number of microplastics was recalculated by removing the verified non-plastics. The microplastics were classified into four morphotypes: fiber, pellet, film and fragment (Li et al., 2016). A fiber was defined as a microplastic with a slender and greatly elongated appearance; pellets were round microplastic with a spherical shape; a film was a small and very thin layer or a piece of large plastic debris; a fragment was an isolated or incomplete part of large plastic debris. The classification of fragment was used, when a microplastic could not be classified as a fiber, pellet or film.

2.5. Verification of microplastics using μ-FT-IR and SEM/EDS

The verification of microplastics using a μ-FT-IR microscopy followed the method describe by Yang et al. (2015). All spectra were compared with a data base (Hummel Polymer and Additives, Polymer Laminate Films, Cross Sections Wizard, HR Spectra IR Demo, Aldrich Vapor Phase Sample Library) to verify the individual plastic item. For SEM observation, samples were spread on double-sided adhesive tape and coated with a thin film of evaporated gold. The morphology of the samples was examined using a SEM (Hitachi S-4800, Japan). The images were taken with an optimized acceleration voltage of 3 kV and detector working distance of approximately 2 mm. Subsequently, qualitative elemental composition of particles was confirmed using an EDS (EMAX).

2.6. Analysis of total phosphorus/nitrogen in water and grain size of the sediments

The concentrations of total phosphorus and total nitrogen in water samples were analyzed using spectrophotometric analysis after digestion according to the national standard for surface water quality. Sub-samples of sediments in each sampling site (10 g wet weight) were treated with 30% hydrogen peroxide solution for 24–48 h to digest organic materials, and then the analysis of sediment grain size was conducted in the laboratory using an LS-100 particle size analyzer. The sediment components were classified into clay (8–12 μ), silt (4–8 μ) and sand (1–4 μ) based on the Udden-Wentworth grain size classification.

2.7. Data analysis

The difference between the quantities of microplastic for more
than two groups was determined by one-way analysis of variance (ANOVA) followed by Tukey’s HSD test (homogeneous variances) or the Tamhane-Dunnett test (heterogeneous variances), along with multiple comparisons. A significance level of 0.05 was chosen, and the difference between two groups was analyzed using Student’s-T Test. The concentrated factor, a dimensionless value, defined as the relative ratio of the abundance of microplastics in organism to sediment, was used to depict the degree of bioaccumulation in the clams living in sediment.

3. Results

3.1. Water quality and grain size of sediments in Taihu Lake

The concentration of total phosphorus was highest in the northwest area of Taihu Lake, followed by the central area. The concentration of Chl-α in the northwest area was also significantly higher than that in the southeast area (Supplementary materials Table 2). Silt dominated the sediments of Taihu Lake, accounting

![Fig. 2. Abundance and spatial distribution of microplastics detected in plankton net (A), surface water (B) and sediment (C) samples collected from the northwest area (NWA), the central area (CA) and the southeast area (SEA) of Taihu Lake in August 2015. * means p < 0.05.](image-url)
for 65–80% of total sediment particles. The distribution of grain size showed little variance among different sites.

3.2. Abundances of microplastics in Taihu Lake

The background contamination represented 6.8% of the average abundance of microplastic detected in field samples. The distribution of microplastic pollution showed significant spatial variations among different sites in Taihu Lake. The abundance of microplastic was $0.01 \times 10^6$–$6.8 \times 10^6$ items/km$^2$ in plankton net samples (Fig. 2A1). For plankton net samples, the average abundance of microplastics in the southeast area was approximately six times higher than that in central area ($p < 0.05$). The abundance of microplastic was $3.4$–$25.8$ items/L in surface water samples and showed less spatial variance than the plankton net samples (Fig. 2B1). The abundance of microplastics was $11.0$–$234.6$ items/kg dw in sediments (Fig. 2C1). The average abundance of microplastics in sediments from the northwest area was approximately six times higher than that of the northwest area ($p < 0.05$).

The maximum and minimum microplastic levels across the three sites were $1.3$–$12.5$ items/g ww in clams in August (Fig. 3A1) and $0.2$–$9.6$ items/g ww in November (Fig. 3B1). There was no significant difference in the abundance of microplastics between August and November (Paired T-Test, $p > 0.05$). For the spatial distribution, the average microplastic pollution burden was the highest in clams from the northwest area in August and November.

3.3. Shape, color and size of microplastics in Taihu Lake

Fiber was the most dominant component across all sample types with a proportion of 48–84% ($p < 0.01$) (Fig. 4A). Blue items were prevalent in plankton net samples and surface water samples, accounting for 50–63% of microplastics ($p < 0.01$) (Fig. 4B). White and transparent items were more common in sediments and organisms, accounting for 29–44% of microplastics. Within the larger size range from 5 to 5000 μm, microplastics with a size of 100–1000 μm were more frequently observed than other size fractions in surface water, sediments and organisms ($p < 0.01$) (Fig. 4C). Within the range from 333 to 5000 μm, microplastics with a size of 333–1000 μm were dominant in plankton net samples ($p < 0.01$).

3.4. Validation of microplastics

The identification of microplastics was validated using spectroscopic methods (Fig. 5). Of all 113 randomly selected items, 81 items were identified as microplastics using μ-FT-IR (Supplementary materials Table 3). For all samples, the most common type of plastic was cellophane, followed by polyethylene.
4.1. Microplastic pollution levels and characteristic in Taihu Lake

Our results suggested that the water, sediment and organisms of Taihu Lake have all been polluted by microplastics. In comparison with worldwide investigations of microplastic pollution in freshwater systems, the abundance of microplastics in plankton net samples was almost two orders of magnitude higher than those in Laurentian Great Lakes of the United States and Lake Hovsgol of Mongolia (Eriksen et al., 2013; Free et al., 2014). To our best knowledge, the levels reported in this study are the highest for freshwater lakes worldwide (Supplementary materials Table 4). The levels of microplastic pollution in the clams from Taihu Lake (0.2–12.5 items/g ww) were similar to those in bivalves from China (0.9–10.5 items/g) (Li et al., 2015a, 2016). In a worldwide comparison, these bivalves have been classified as highly polluted organisms by microplastics (Li et al., 2015a, 2016). The average level of microplastics in Taihu Lake clams was much higher than that in bivalves (0.36 items/g) cultured for human consumption (Van Cauwenberghie and Janssen, 2014). Therefore, the results of our present strongly suggest that high levels of microplastics occur not only in the water of Taihu Lake but also in organisms present in the lake.

It is reasonable to find much higher levels of microplastics in the lakes in areas with intensive anthropogenic activities (Eriksen et al., 2013). However, high levels of microplastics have even been found in a remote mountain lake of Mongolia (Free et al., 2014). There are 22 main influent rivers connecting the lower Yangtze River area to Taihu Lake (Wang et al., 2015), and three of these rivers connected to the northern bay contribute 1/3 of the total inflow to Taihu Lake (Fig. 1). These rivers are spread across the most developed regions in the Taihu Basin and carry contaminants from drainage and industry. These rivers are therefore identified as the major contributors of contamination to the lake (Li et al., 2013). In the vicinity of Taihu Lake, cities with a high population density (e.g., Suzhou, Wuxi and Changzhou) are also suspected sources of the microplastic pollution because of the huge amounts of effluent and waste, that may enter the lake through rivers and non-point sources (Li et al., 2015b). In particular, the high relative abundance of fibers in this study indicates domestic microplastic sources, such as washing machines (Browne et al., 2011). Even if waste water treatment plants are able to remove microplastics from their effluent (Carr et al., 2016), waste water originating from rural non-point sources has no treatment and will still constitute a significant source of water pollution to Taihu Lake (Wang et al., 2010).

The fishing industry plays an important economical role in the Taihu Lake area, with the total aquatic products reaching 30,000 tons per year (Chen and Zhu, 2008). The Asian clam is one of the most popular freshwater shellfish and one of the most commonly cultured species in the middle and lower reaches of the Yangtze River as well as in Taihu Lake. Accumulating evidence has suggested that microplastics can bring adverse effects on energy metabolism, immunity and even reproduction of organisms (Wright et al., 2013; Sussarellu et al., 2016; Galloway and Lewis, 2016). Microplastics can also be retained through the food chain and enter human bodies through diverse pathways (Farrell and Nelson, 2013; Seltenrich, 2015; Yang et al., 2015). Therefore, we need to pay close attention to the high levels of microplastic contamination in Taihu Lake and any possible human health risk from consumption of fishery products.

In the present study, cellophane was the dominant particle. Cellophane is a typical semi-synthetic material because a lot of additives have been added to the products. It shows low biodegradability though it is biomass derived. It was even not destroyed by hydrogen peroxide in this study. Synthetic polymer from biomass derived is also regarded as microplastic in a recent report of UNEP (2016). Cellophane has been defined as microplastic in previous studies (Denuncio et al., 2011; Yang et al., 2015). Many plastics labelled as biodegradable will break down completely only when subjected to prolonged temperatures above 50 °C, and biodegradable plastic seems to be a “false solution” for ocean waste problem (UNEP, 2016). Therefore, cellophane was defined as microplastic in the present study.

4.2. Spatial features of microplastic pollution in Taihu Lake

The abundance of microplastics showed great spatial variability within the same type of sample (e.g., plankton net samples). There were no consistent results for the spatial distribution of microplastics. SEM/EDS. The abundance of microplastics showed great spatial variability within the same type of sample (e.g., plankton net samples).
was also considerable variation between different samples collected within the same area. Microplastic levels are known to be correlated with anthropogenic activities (Cole et al., 2011; Barboza and Gimenez, 2015). In Taihu Lake, the index of eutrophication has a close relationship with the level of pollutant inflow, which also greatly depends on anthropogenic activities (Zhang et al., 2008). According to the index of eutrophication in this study, the northwest area of the lake was heavily polluted, and the southeast area was relatively clean. These area-specific contamination patterns match well with previous studies on other chemical pollutants in Taihu Lake, such as heavy metals (Liu et al., 2012; Yu et al., 2012). In this study, more microplastic could come from the northwest area of Taihu Lake than from the southeast area due to the inflows of different pollutants. Eutrophication can also decrease the light penetration depth and result in less plastic degradation in lakes (Andrady et al., 2011; Free et al., 2014). Therefore, further studies are needed to illuminate the effects of accumulation of microplastic in the water of eutrophic lakes.

The highest abundance of microplastics in plankton net samples was observed in the southeast area of Taihu Lake. This distribution of microplastic is odds with the hypothesized of microplastics from the different areas of Taihu Lake. Previous studies have suggested that floating plastics are likely affected by meteorological conditions (Browne et al., 2011; Free et al., 2014; Fischer et al., 2016); Specifically, strong wind can increase the dissipation of floating microplastic (Collignon et al., 2012). Generally, the hydrodynamics processes are the poorest in the southeast area of Taihu Lake based on the characteristics of wind and wave of the whole lake regions, and the wind speed was less than 2 m/s in southeast area during the sampling period in Taihu Lake. Therefore, a minor disturbance in meteorological and hydrological conditions could result in an increase in the accumulation of floating microplastics and be responsible for the high abundance observed in the southeast area.

Unlike in plankton net samples, the abundance of microplastics in sediments was the lowest in all three sites located in the southeast area, and there was a clear trend, increasing from the southeast to the northwest area of the lake. This trend matched well with the chemical contaminants (Supplementary materials Table 2). The microplastics can be carried from the rivers, float in the surface water, stay in the water column or sink into sediments of the lake. The sediments were more stable than water, and microplastics in the sediments will be transported more slowly than those floating in surface water. Therefore, the microplastic pollution levels in sediments from the lake were more closely related to the distance from the contamination source as mentioned above.

4.3. Bioaccumulation of microplastics in clams and biomonitoring of microplastics in freshwater

In the present study, Asian clams were available at most of the sampling sites in Taihu Lake. No significant differences were found in the presence of microplastics in clams among the different areas of the lake (Fig. 6). The concentrated factor ranged from 38 to 3810 and was negatively correlated with the abundance of microplastics in sediments (p < 0.05). In laboratory studies, the bioaccumulation of microplastics has been proved to occur in coastal invertebrates even when the background concentration of microplastics is relatively low (Setälä et al., 2016). Our results suggest that clams showed a higher concentrated factor when the abundance of microplastics was lower in lake sediments. This phenomenon might be one of the reasons why the abundances of microplastics in clams showed no significant differences in different areas of the lake.

Bivalves are of particular interest in microplastic studies and monitoring because their extensive filter-feeding activity exposes them directly to microplastics present in aquatic environments (Farrell and Nelson, 2013; Li et al., 2015a; Sussarellu et al., 2016). Clams are representative benthic filter feeders and a diet item of many other benthic species. The Asian clam originates in Asia and can now be found worldwide (Sousa et al., 2008). It has a wide range of habitats from freshwater (e.g., river and lake) to estuarine environments. It has been successfully used in the biomonitoring of emerging contaminants (e.g., nanoparticles) owing to the advantages stated above (Pereira et al., 1999; dos Santos and Martinez, 2014; Cid et al., 2015). Our findings suggest that microplastics are not only ingested by benthonic organisms but are also likely to accumulate in clams to a great extent. The large concentrated factor
indicated that Asian clams could also be an ideal indicator of microplastic pollution in freshwater and estuarine environments. Nevertheless, larger-scale investigations on microplastics are still required to validate this proposal of clams in the future.

In conclusion, we found that high levels of microplastics occurred not only in the water but also in the organisms of Taihu Lake. To our best knowledge, the microplastic levels found in Taihu Lake were the highest in plankton net samples in freshwater lakes worldwide. We need to pay close attention to the microplastic contamination in Taihu Lake and the possible link to human health risks resulting from the consumption of fish products. We propose that the widespread Asian clam could serve as a useful bio-indicator for microplastics pollution in freshwater and estuarine environments.

Notes

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.envpol.2016.06.036.

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