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Vertical distribution of microplastics in the sediment profiles of the Lake Taihu, eastern China

Yinan Huang^{1,2}, Jiajia Fan^{2*} , Huan Liu³ and Xiancai Lu³

Abstract

Microplastics are ubiquitous in the freshwater environment, while its abundance in the sediment profiles has received little attention. The vertical microplastic distribution in the sediment of the North (NTH) and Southwest (SWTH) of Lake Taihu was identified and characterized in this study. Microplastics could be detected at all depths (0–50 cm) at the two sites, with the total abundance of 8100 and 5300 particles kg^{-1} dry weight sediment at NTH and SWTH, respectively. This indicates that the microplastic storage in the sediment of the Lake Taihu may be underestimated, if only the surface sediment is considered. Microplastics composed of various polymer types were identified in the sediment of the two sites, including polyamide (PA), acrylic acid, polyethylene terephthalate and cellulose acetate, while high density polyethylene and polypropylene were only detected at NTH. The main type of polymers detected at NTH (42%) and SWTH (43%) were PA. The major shape of microplastics was fibers, with a ratio of 76% and 78%, respectively at the site NTH and SWTH. The colors of microplastics were mainly white (accounted for 42 and 43% at NTH and SWTH, respectively), which may be caused by the long-term decomposition of dyestuff in the syngensis of sediment and/or probably the degradation during sample treatments. The textile industry and fishery activities may provide the source. In summary, our findings in the Lake Taihu provide better understanding of the microplastic pollution and tackle microplastics challenges.

Keywords: Microplastics, Sediment, Vertical distribution, Raman, The Lake Taihu

1 Introduction

Plastics is a synthetic organic polymer, which is widely used worldwide due to its durability and low price. The production of plastics has been increased around 20 times in the last 50 years all over the world [1]. Although the plastic litter composed from large pieces can be removed and recycled from the environment, a great number of plastic fragments may be easily transported into aquatic environments [2]. Small plastic fragments with a size of less than 5 mm are defined as microplastics

[3], and they are distributed in various areas, such as seawater, groundwater and living organisms [4–6]. Microplastics can cause various harm to organisms, due to their physical and chemical properties [6, 7]. For instances, it has been reported that organic pollutants (e.g., polychlorinated biphenyls and tetracycline) and heavy metals can be tightly adsorbed to the surface of microplastics, which may damage the organisms (e.g., gut blockages) [6, 7]. Moreover, studies have shown that microplastics could be detected in human bodies [8, 9], resulting in various adverse effects, such as the production of high reactive oxygen species in the epithelial cells of human bodies [9]. Consequently, according to the risk of microplastics to human health, it is necessary to study

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their distribution in lake sediment close to densely populated area.

The literatures on microplastics have gradually increased during recent years, accompanying with the understanding of microplastic risks. In particular, a great number of studies have shown that large quantities of microplastics are detected in various marine water and sediment [4, 10]. However, there are relatively fewer studies on microplastics in freshwater bodies (e.g., rivers and lakes). The pollutants in marine sediment mainly come from terrestrial environments through surface runoff, from the adjacent coastal areas [4]; while the majority of microplastics in lake sediment is generally sourced from surrounding areas. Hence, it will be helpful to understand microplastic pollution in the nearby lake-watershed through studying the spatial distribution of microplastics in lake sediment [2]. In addition, the vertical distribution of microplastics can reflect its historical input via ^{210}Pb isotope dating.

Recently, microplastics have been detected in different depths of various marine and lake sediment (e.g., Southern Ocean regions, the Tokyo Bay, Gulf of Thailand, and the Wuliangsu Lake in China) [2, 11, 12]. Studies have shown that microplastics may be preserved in deep sediment, and the amounts may be even larger than surface sediment and overlying waters [13, 14]. For instances, a study by Xue et al. [13] has documented that the storage of microplastics in the sediment (5 to 60 cm) is 5 times more than that in the surface sediment in the Beibu Gulf of China. Another study has indicated that the abundance of microplastics was about 250 particles kg^{-1} dry weight (DW) at both of the depth of 17 and 37 cm in an urban pond in North London [15]. Therefore, the total amounts of microplastics in the sediment may be considerably larger than it was only concluded from surface sediment. Consequently, it is necessary to evaluate the distribution of microplastics in vertical profiles of sediment.

The Lake Taihu is the third largest freshwater lake in China. It has suffered various environmental pollution during recent decades, including algal blooms, the contamination of heavy metals and organic pollutants [16, 17]. Recent studies have also shown that microplastics could be detected in a wide range area of the Taihu [14, 18, 19]. To date, the reported studies mainly focus on the distribution of microplastics in the surface sediment of the Taihu [14, 18], while the research on the vertical distribution of microplastics in the sediment of this lake is rare. To contribute to the better understanding of microplastic pollution in the Taihu, this study investigated the vertical distribution of microplastics in the sediment profiles at two sampling sites. The objectives of this study were to: 1) extract microplastics from the sediment samples at different depths, and characterize

their sizes, colors, shapes and compounds; and 2) discuss the main sources of microplastics in the Taihu, based on their vertical distribution detected in this study and data from previous studies.

2 Materials and methods

2.1 Sampling sites

The samples were collected on the April 14th, 2019 from the drills at two sites in the Taihu (Fig. 1). One site is located in the northern area (30°55'40" N, 119°52'32" E, near the Meiliang Bay), which was marked as NTH. The other site is located in the southwestern area (31°32'58" N, 120°36'10" E), which was marked as SWTH. The sediment were sampled using pushcores (VC-D SDI, America) with a length of 1 m and the diameter of 73 mm, which could enter the sediment by pressing the hand level. The coring process was controlled to be slow, which could minish the sediment compression to the utmost extent. These pushcores were made of transparent acrylic tubes (PETG, America), which were reported to avoid the contaminations for sampling and were widely used to collect sediment for study on microplastics [11, 20]. Cores were capped immediately and wrapped with aluminum foil on board. The samples were separated 4.0 cm intervals in the depth range of 0–20 cm, and 5.0 cm intervals in 20–50 cm.

2.2 Extraction of microplastics

A density separation method was used to extract microplastics referring to a previous study by Nuelle et al. [21], with slight modifications. Since the surface of the sediment samples cover with large amount of organic matter, which will disturb the characterization of the microplastics, the samples should be treated with hydrogen peroxide (H_2O_2) [21]. A previous study showed that under the treatment of 30% H_2O_2 for seven days, the sizes of microplastics decreased by less than 10% within the period, and many microplastics became discolored [21]. Hence, 30% H_2O_2 has little impact on the size of microplastics, but it will turn microplastics into white color during the experiment process. Therefore, the contact of the H_2O_2 with the microplastics needs to be minimized.

A certain amount of wet sediment was wrapped in aluminum foils and dried at 40 °C in a vacuum drying oven, ensuring each dried sample was more than 15.0 g. The dried sample (15.0 g) was weighed and transferred into a beaker, then calcium chloride solution (5 L, $\rho=1.6 \text{ g mL}^{-1}$) was added in to the beaker, followed by evenly stirring and standing for 12 h [22]. The supernatant was transferred to a 50 mL centrifuge tube, then sodium iodide solution (6 mol L^{-1} , 0.5 mL) was added to the tube to achieve a suspension density of 1.6 g mL^{-1} . The tube was centrifuged at 3000 r min^{-1} for 10 min to

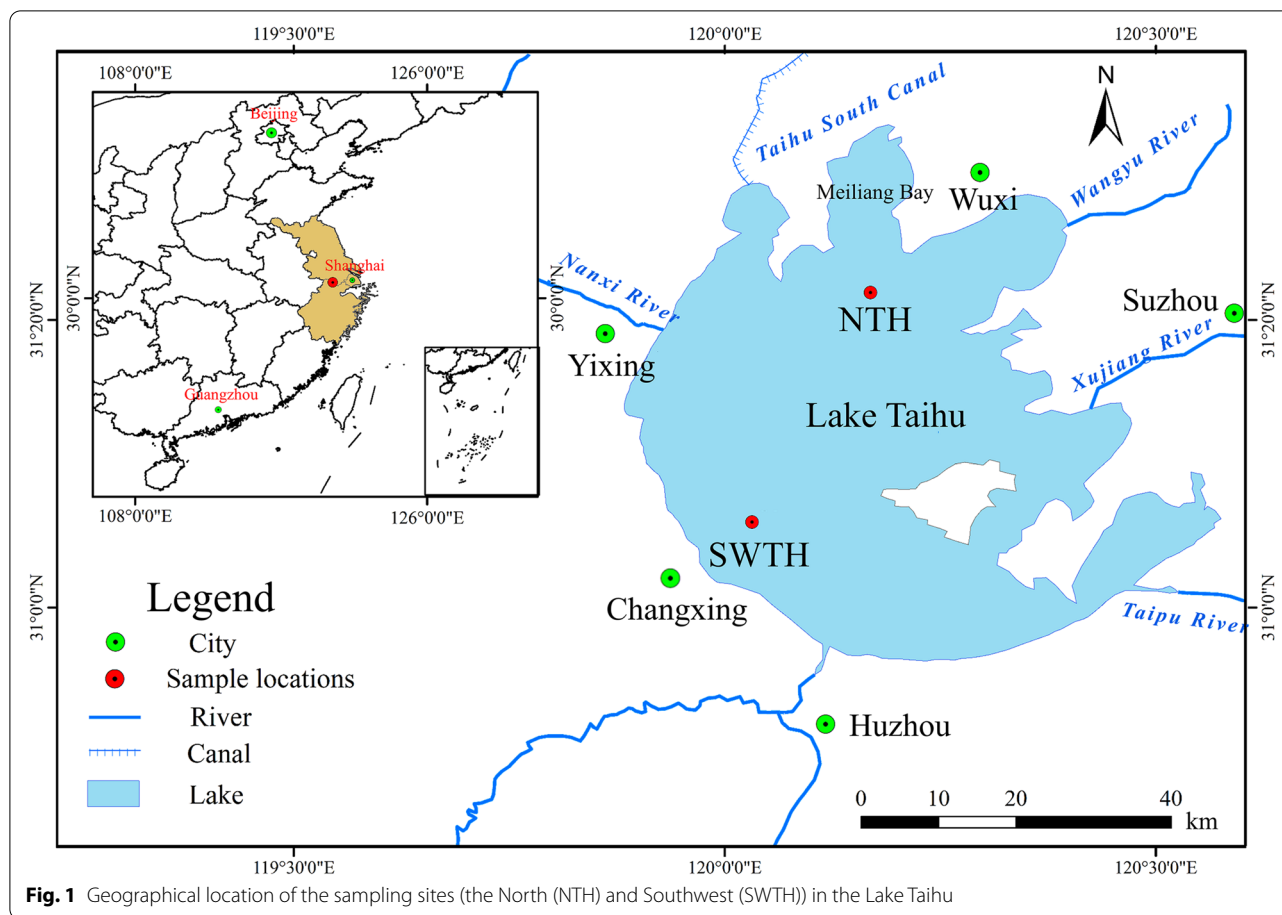


Fig. 1 Geographical location of the sampling sites (the North (NTH) and Southwest (SWTH)) in the Lake Taihu

collect the supernatant. The supernatant was then filtered through a mixed cellulose esters membrane (Xinya, China) with a pore diameter of 0.3 μm , the membrane was placed in a beaker and air-dried at room temperature. H_2O_2 (30%) was added to the beaker to completely submerge the membrane for about 12 h until no more bubbles evolved, to remove most of the organic matters. The suspension was filtered through a mixed fiber membrane ($\phi=0.3 \mu\text{m}$), then the membranes were air-dried at room temperature for observation.

2.3 Characterization of microplastics

A stereo microscope (SMZ25 Nikon, Japan) was used to distinguish and categorize microplastics according to their shapes, colors and sizes. In general, fiber, fragment, pellet and film are four common types of microplastic shapes. Microplastics were measured and categorized into four types according to their sizes: < 250, 250–500, 500–1000, and 1000–5000 μm .

Raman spectroscopy (LabRAM HR Evolution Horiba, Japan) was used to further determine the composition of microplastics. Representative particles of potential microplastics in each layer of the samples were selected

for Raman analysis, based on stereo microscope. The scanning range was 500–3500 cm^{-1} with a step of 2 cm^{-1} . In particular, three types of excitation wavelengths of 785, 633 and 532 nm were selected to avoid the effects of fluorescence emission. A scanning electron microscope (SEM, Gemini 500 Zeiss, Germany) was also used to observe the morphology of microplastics. All of the observation and Raman spectra were compared with previous literatures and the Raman spectral databases, to determine the composition of the microplastics.

2.4 Dating determination

The dried sediment samples were first ground to 100 mesh (0.149 mm), and then 5 g of each sample was used for radioisotope measurement. ^{210}Pb and ^{226}Ra activities were detected via gamma spectrometry using an Ortec HPGe GWL series well-type coaxial low background intrinsic germanium detectors [23]. Theoretically, the excessive ^{210}Pb ($^{210}\text{Pb}_{\text{exc}}$) exponential decreases with the sediment depth. The $^{210}\text{Pb}_{\text{exc}}$ was obtained by subtracting the activity of ^{226}Ra from the total activity of ^{210}Pb ($^{210}\text{Pb}_{\text{tot}}$).

2.5 Contamination control

Following quality assurance and quality control measures were employed in this study, according to previous studies [2, 22]. To prevent possible contamination, cotton and nitrile gloves were worn during sediment sampling and the experimental procedures, respectively. Cotton clothes were worn to prevent contamination, all containers were washed with distilled water and covered with aluminum foil to reduce contamination. Before identification and quantification of the microplastics, the sample holders of the stereomicroscope and Raman spectroscopy were carefully cleaned and inspected. During the procedures of sample drying and observation, the filter membrane inevitably exposed to the air, thus, blank experiment was conducted in triplicate to verify whether there was any microplastic interference [2]. Only a small amount of microplastics (0.67 particles filter⁻¹ on average) were found in the blank sample, then the experiment data were corrected according to the results of the blank experiment.

3 Results

3.1 Shapes and distribution of microplastics

The sampled sediments in the Taihu were dark gray. Laminae structure cannot be identified in the surface sediment (0 to 15 cm), however, micro-laminae structure could be observed in deeper sediment, and their

thickness ranges 0.30–0.55 cm with an average of 0.42 cm (Fig. S1 in the Supplementary Materials). Total ²¹⁰Pb in the studied core declined from 204 Bq kg⁻¹ at shallow region to 103 Bq kg⁻¹ at the depth of 40 cm. The age of the core was calculated based on the decay profile of ²¹⁰Pb_{exc} activity (Fig. 2a) and the constant rate of supply model [24]. The results showed that the age of the sediment at 40 cm was about 120 years, and the average sedimentation rate in the study area was about 3.3 mm y⁻¹. An obvious inflection point exists at about 20 cm, above which the average sedimentation rate was about 6.7 mm y⁻¹ and below which the average rate was about 2.2 mm y⁻¹, indicating a transition of sedimentary environment.

Four different colors of fibers were found in the sediment, which were marked as white, black, red and blue fiber, respectively (Fig. 3). Fibers are the dominant microplastics (approximately 74%) at NTH, with an amount of 5900 particles kg⁻¹ DW (Fig. 3a). Blue, white, black and red fibers were observed at NTH (Fig. 3a). In particular, the blue fibers were found at all depths, with a total abundance of 1900 particles kg⁻¹ DW. White was the dominant color in fibers (39%), mainly distributing at the depth ranging from 16 to 50 cm, with an abundance varied from 200 to 600 particles kg⁻¹ DW. Other shapes of microplastics were also detected, including film, fragments and pellets (Fig. 4). Film (about 1400 particles kg⁻¹ DW) were

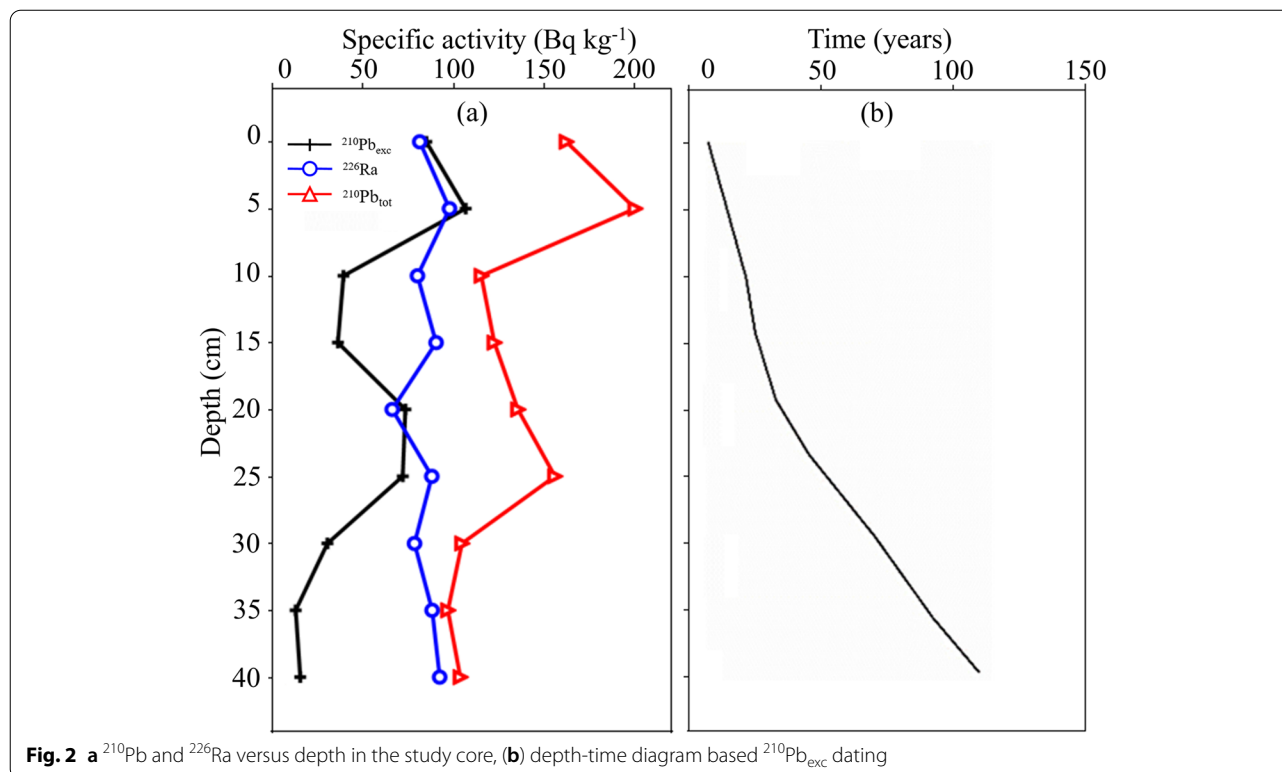
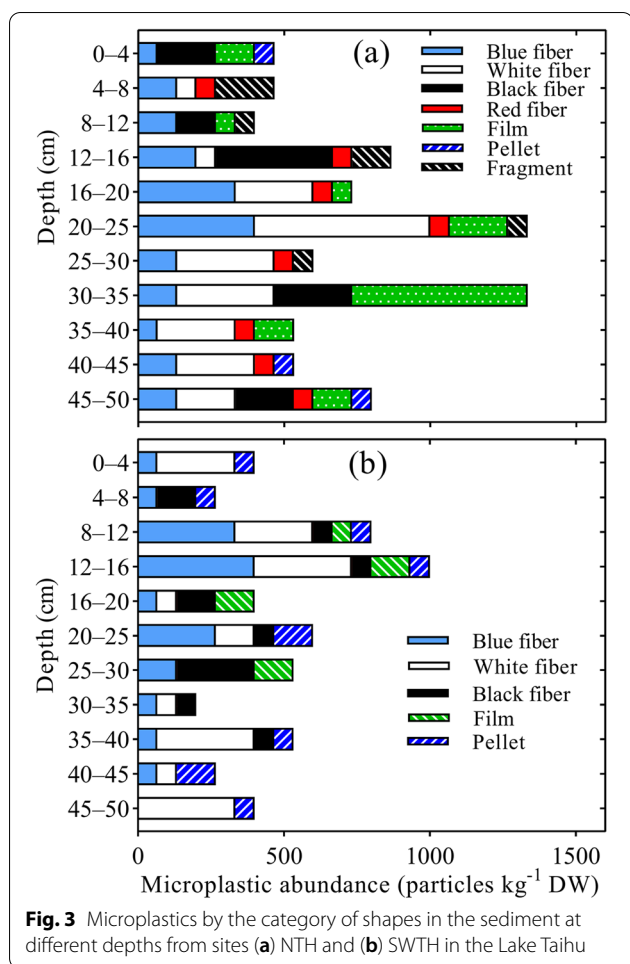


Fig. 2 a ²¹⁰Pb and ²²⁶Ra versus depth in the study core, (b) depth-time diagram based ²¹⁰Pb_{exc} dating



found at most of the depths (Fig. 4d), in particular, there was a high abundance (600 particles kg⁻¹ DW) observed at the depth of 30–35 cm. The total abundance of fragments and pellets were only 530 and 200 particles kg⁻¹ DW, respectively. Pellets were found in the deep sediment (45–50 cm), whereas fragments were only observed in the 0–30 cm layers (Fig. 4a).

Similar to the samples at the site NTH, fibers also contributed to the highest microplastic abundance (approximately 78%) in the sediment of the site SWTH, while the amount was lower (4200 particles kg⁻¹ DW) (Fig. 3b). In particular, blue (34%) and white (43%) were the dominant colors of the fibers, which distributed in the majority layers of the sediment, while there was no red fiber found at SWTH. The total abundance of film at SWTH was apparently lower (460 particles kg⁻¹ DW) than those at the site NTH, and none of fragments was observed at SWTH. However, the total abundance of pellets were 670 particles kg⁻¹ DW, which were higher than that at NTH (Fig. 4c).

3.2 Size distribution and abundance of microplastics

Microplastics were observed in all the sediment samples at both sites (Fig. 5). The results showed that the total abundance of microplastics was 8100 particles kg⁻¹ DW sediment (0 to 50 cm) at the site NTH (Fig. 5a). The abundance of microplastics at depths ranging from 12 to 35 cm varied from 730 to 1300 particles kg⁻¹ DW, which was considerably higher than those in the surface sediment (0 to 12 cm). The amounts of microplastics at deeper depths (35–40 and 40–45 cm) were also lower than that in the 12–35 cm layers, with 530 particles kg⁻¹ DW in each layer. However, a large storage of microplastics (800 particles kg⁻¹ DW) was detected in the deepest layer (45–50 cm). In the samples from the site NTH, the microplastics with size < 250 μm contributed to the highest abundance (32%), with a total amount of 2600 particles kg⁻¹ DW (Fig. 5a). The microplastics with the size classes of 250–500, 500–1000 and 1000–5000 μm accounted for 26, 19 and 24% of the storage, respectively. In particular, microplastics in the 250–500 μm size range contributed to the highest abundance (45%) in the 35 to 50 cm layers of the sediment (Fig. 4f).

The abundance of microplastics in the sediment at SWTH was apparently lower, compared to that at NTH (Fig. 5b), with the total amount of 5300 particles kg⁻¹ DW at the depth ranging from 0 to 50 cm. The microplastics with a storage of 670 particles kg⁻¹ DW was detected in the surface sediment (0–8 cm). The highest abundance of microplastics (1000 particles kg⁻¹ DW) was observed in the 12–16 cm layer. In general, the abundance of microplastics in the sediment at SWTH has shown no consistent trend from the surface to the bottom layers. The microplastics with the size class of 1000–5000 μm contributed to the largest abundance, with a total amount of 1700 particles kg⁻¹ DW in the sediment (Fig. 4h). The amounts of microplastics with the < 250, 250–500 and 500–1000 μm size ranges were similar, which slightly varied from 1200 to 1400 particles kg⁻¹ DW (Fig. 4g).

3.3 Polymer types of microplastics

Typical Raman spectra of the isolated microplastic samples were collected, the analyzed points were selected based on microscopic observation (Fig. 6; Fig. S2). The chemical composition of the microplastics was determined referring to the microplastic Raman spectral library (Fig. 7; Fig. S2). Three types of representative microplastics and their comparison with standard polymers were presented (Fig. 7). The identification of polypropylene (PP), high density polyethylene (HDPE), polyamide (PA), acrylic acid (AA), polyethylene terephthalate (PET) and cellulose acetate (CA) were also characterized by their unique peaks

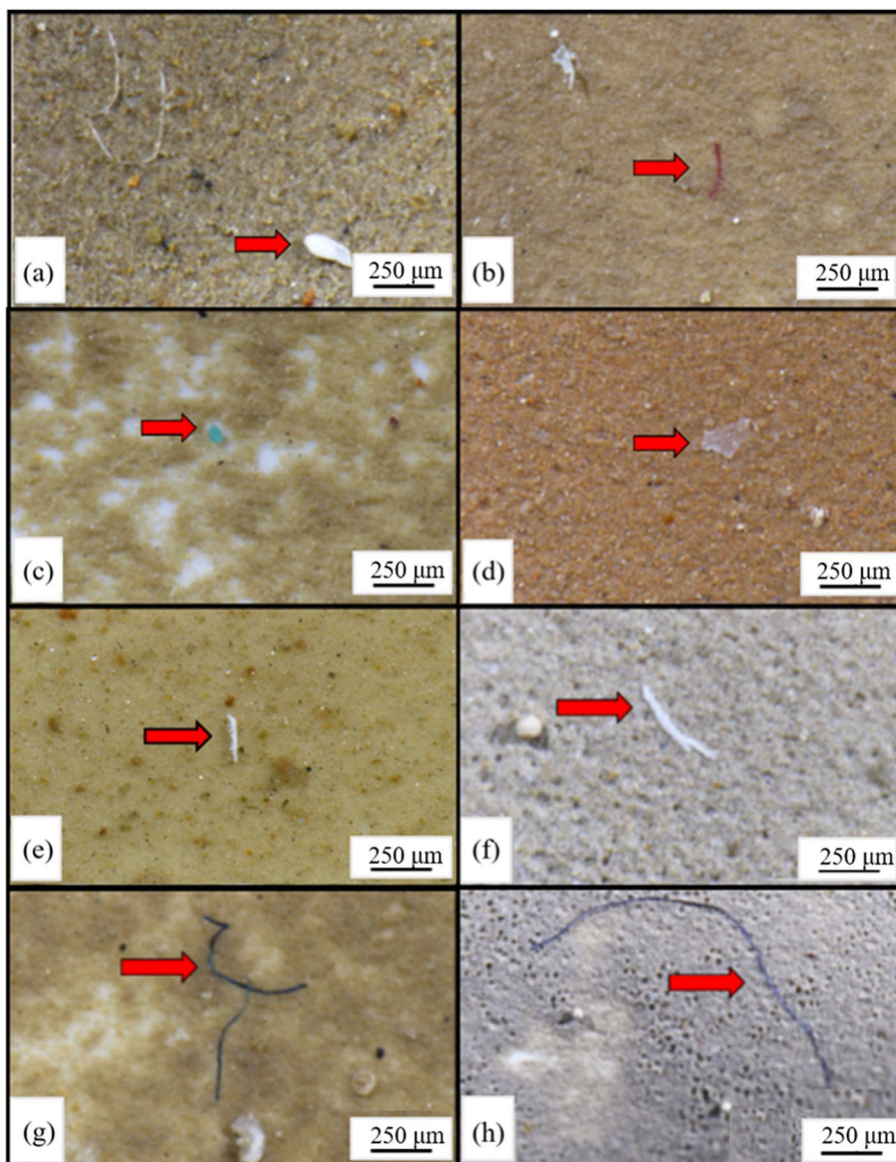


Fig. 4 Photographs of typical microplastics collected from the sampling sites. The photos are corresponding to (a) fragment; (b) fiber; (c) pellet; (d) film; (e) <math> < 250 \mu\text{m}</math>, from the 0–4 cm layer of the NTH; (f) 250–500 $\mu\text{m}</math>, from the 12–16 cm layer of the NTH; (g) 500–1000 $\mu\text{m}</math>, from the 20–25 cm layer of the SWTH; and (h) 1000–5000 $\mu\text{m}</math>, from the 4–8 cm layer of the SWTH. The sands in the microscopic domains were separated from the sediment$$$

(Fig. 7b and c; Fig. S2), e.g., PET microplastics were characterized by the peaks at 857, 1727 cm^{-1} and the region from 2800 to 3100 cm^{-1} (Fig. 7a) [25]. However, in Raman spectra, weak signal may be embedded in strong interference because of the fluorescence and impurities. Therefore, SEM analysis was further used to characterize samples as a supplementary method. For example, the entangled filamentous structure could be observed by SEM, which was one of the typical characteristics of AA (Fig. 8b). Similarly, other

typical microplastics were also identified based on the SEM images (Fig. 8; Fig. S3).

There were five types of microplastics identified by Raman spectra. For the samples at NTH, 42% of the analyzed particles were identified as PA, 24% as AA, 23% as PET, 4.5% as CA, 3.3% as HDPE, and 2.5% as PP; the unknown particles accounted for 2.4% (Fig. 9a). In particular, PA and AA were distributed in all of the sampling layers, while CA were observed only at the depth ranging from 12 to 30 cm. However, HDPE were only detected

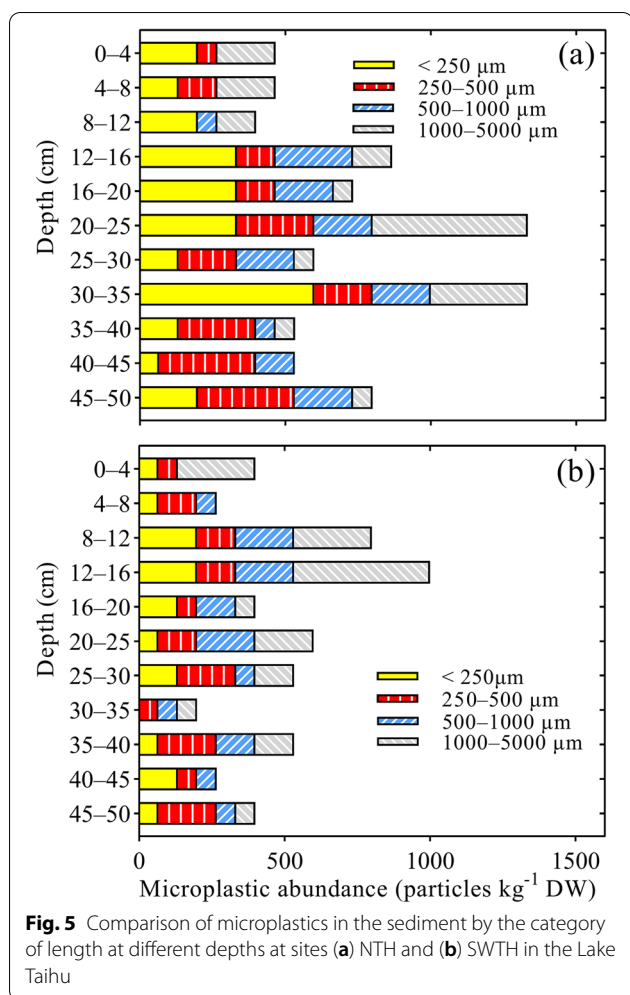


Fig. 5 Comparison of microplastics in the sediment by the category of length at different depths at sites (a) NTH and (b) SWTH in the Lake Taihu

in the surface (0–12 cm) and deep (40–50 cm) layers. PP were only observed in the layers of 20–35 cm at NTH, with the total abundance of 200 particles kg⁻¹ DW.

For the sediment samples at the site SWTH, 43% of the particles were identified as PA, 23% as PET, 10% as CA, 7.5% as AA, and 3.3% as HDPE; and 12.5% of the particles were not identified (Fig. 9b). PA was observed at the majority of the sampling depths, except for the 45–50 cm layer. Compared to the NTH site, the abundance of AA in the sediment of SWTH was considerably lower. There was only a small amount of HDPE (3.3%) observed in the sediment of SWTH.

4 Discussion

4.1 Abundance of microplastics in the vertical sediment profile

Microplastics were detected in each layer of the sediment from the sites NTH and SWTH (Fig. 3). To date, this is the first observation of microplastics from the sediment of the Taihu in the layers of as deep as 50 cm. According

to previous studies, the sedimentary rate at neighboring area ranged in 0.21–0.41 cm yr⁻¹ [26, 27], which is consistent with the observed average thickness of microlamina (0.42 cm). A study by Wu et al. [27] reported an increased sedimentary rate as high as 0.88 mm yr⁻¹ during the past decades in the Northern basin of the Taihu. Therefore, the estimated age of the sediment at the depth of 50 cm can be considered as less than 100 years. Although plastics was industrially synthesized in 1909, it has been extensively used worldwide since the 1950s [28]. Therefore, microplastics may not be detected at the depths below a threshold theoretically [10]. Hydrodynamic perturbation and biological disturbance might be responsible for the vertical transport of microplastics [13, 29]. For instance, a study has reported that tubificid worms may burrow vertical wormholes in the sediment of the Taihu, which may disturb the vertical distribution of microplastics [29].

The abundance of microplastics detected in the surface sediment (0–4 cm) from the sites NTH and SWTH were 470 and 400 particles kg⁻¹ DW, respectively (Fig. 3). It has been documented that microplastics could be found in the surface sediment (0–5 cm) of various regions of the Taihu [14, 18, 19]. In particular, the microplastic abundance in the northern (near the site NTH in this study) and the southwestern areas (near the site SWTH in this study) were approximately 230 and 98 particles kg⁻¹ DW, respectively [14]. However, a recent study by Zhang et al. [14] has reported that the microplastic abundance in the northern and southwestern areas were 790 and 1400 particles kg⁻¹ DW, respectively. The difference of the detected microplastic abundance in the surface sediment may be due to different sampling methods [14, 18].

Previous studies only detected microplastic samples in the surface sediment of the Taihu, without observation of the microplastic abundance in the various depths for each sample site [14, 18]. The results in this study showed that the abundance of microplastics in various lamina of the non-surface sediment (5–50 cm) collected from NTH and SWTH were 6800 and 4700 particles kg⁻¹ DW, respectively, which was significantly higher than that in the surface sediment (0–4 cm). The microplastics may migrate to the overlying water during the process of sampling, causing the underestimation of the microplastic abundance in the surface sediment. Similar vertical distribution of microplastics have been reported in the sediment from other lakes [13, 30]. For instance, Xue et al. [13] have found that the microplastic abundance in the surface sediment (0–5 cm) was 1200 particles kg⁻¹ DW in the Lake Nanliu, China, while the total abundance of microplastics was considerably higher, with a content of 9800 particles kg⁻¹ DW in the sediment (5–60 cm).

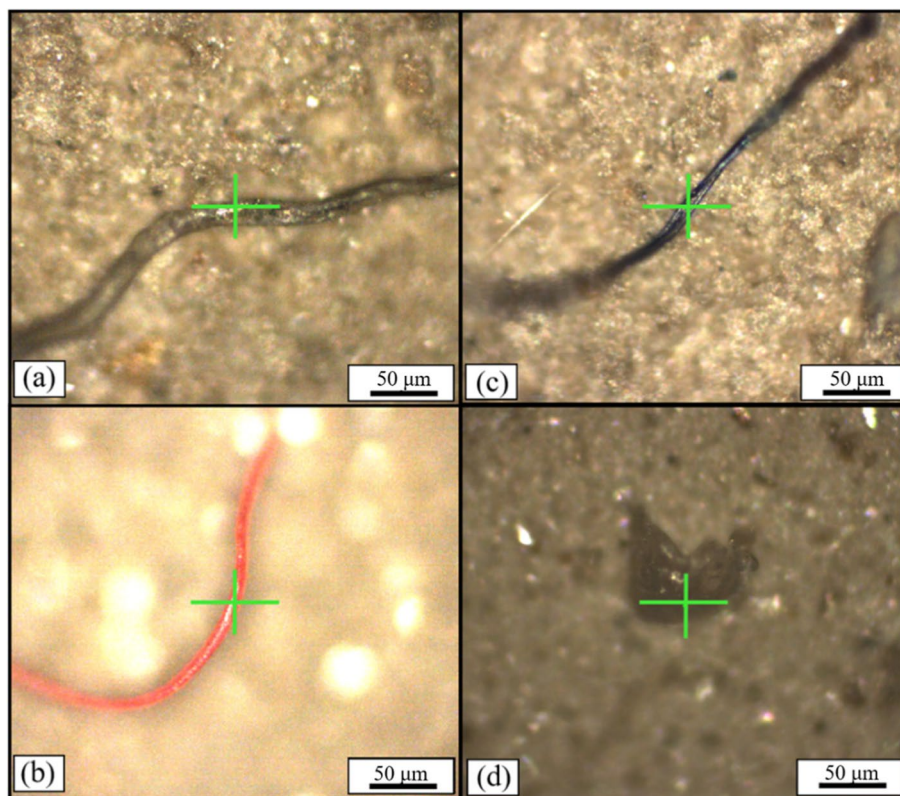


Fig. 6 Photos of microplastics taken using the microscope equipped with Raman spectroscopy, **(a)** acrylic acid (AA), from the 16–20 cm layer of the NTH; **(b)** cellulose acetate (CA), from the 40–45 cm layer of the NTH; **(c)** polyamide (PA), from the 25–30 cm layer of the SWTH; and **(d)** high density polyethylene (HDPE), from the 20–25 cm layer of the SWTH

Thus, the total storage of microplastics in the sediment may possibly be underestimated if only concluded their amounts from the surface sediment.

The microplastics observed at the site NTH presented a higher abundance and diversity than those at SWTH (Fig. 3). The location of the site NTH is close to the Meiliang Bay, which is surrounded by residential, industrial and agricultural regions [14]. These regions may discharge large amounts of microplastics into the aquatic environment [2, 30–33]. For instance, some of the fibers detected may come from the process of laundering in residential regions [30]. Consequently, the high abundance of microplastics at the site NTH may be originated from clothes, fishing nets and agricultural plastic film from its surrounding areas [2, 30–33]. Compared to the areas near the site NTH, there was less pollution around the site SWTH. The abundance of microplastics in the sediment at the site SWTH was rarely reported; however, the large amounts of microplastics detected in this study indicated that the microplastic pollution in this area should be also taken into account.

4.2 Composition of the microplastics in the sediment

In general, polymers are composite materials containing fillers, pigments, and plasticizers; thus, few environmental plastics are pure polymers [34]. Therefore, some studies have identified dyed polymers as microplastics directly [11, 34]. The Raman scattering from polymers may be weak or even covered by the interruption of incorporated dyes, which may lead to the difficulty in distinguishing the composition of polymers by Raman spectroscopy [34]. In order to improve the accuracy in identifying microplastics, SEM was applied in this study to assist the observation by stereo microscope and measurements of Raman spectra. For example, according to the SEM images, the morphology of a particle collected in the sediment of NTH was highly similar to worn fishing lines identified by a previous study; hence, this type of particles was defined as a microplastic fiber in this study (Fig. S3) [35].

The majority of the collected microplastics in the sediment of the sites NTH and SWTH were fibers, with most of them identified as PET and PA (Figs. 3 and 9). Previous studies have also indicated that PET and PA are the

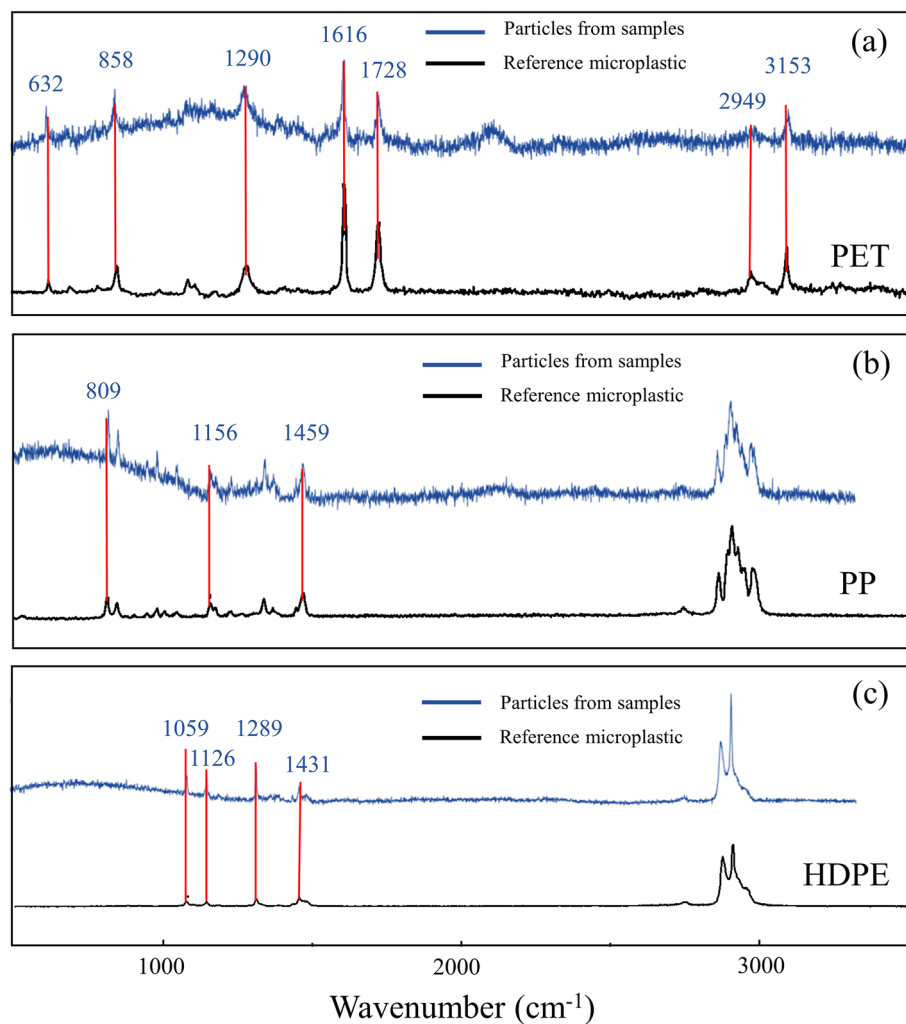
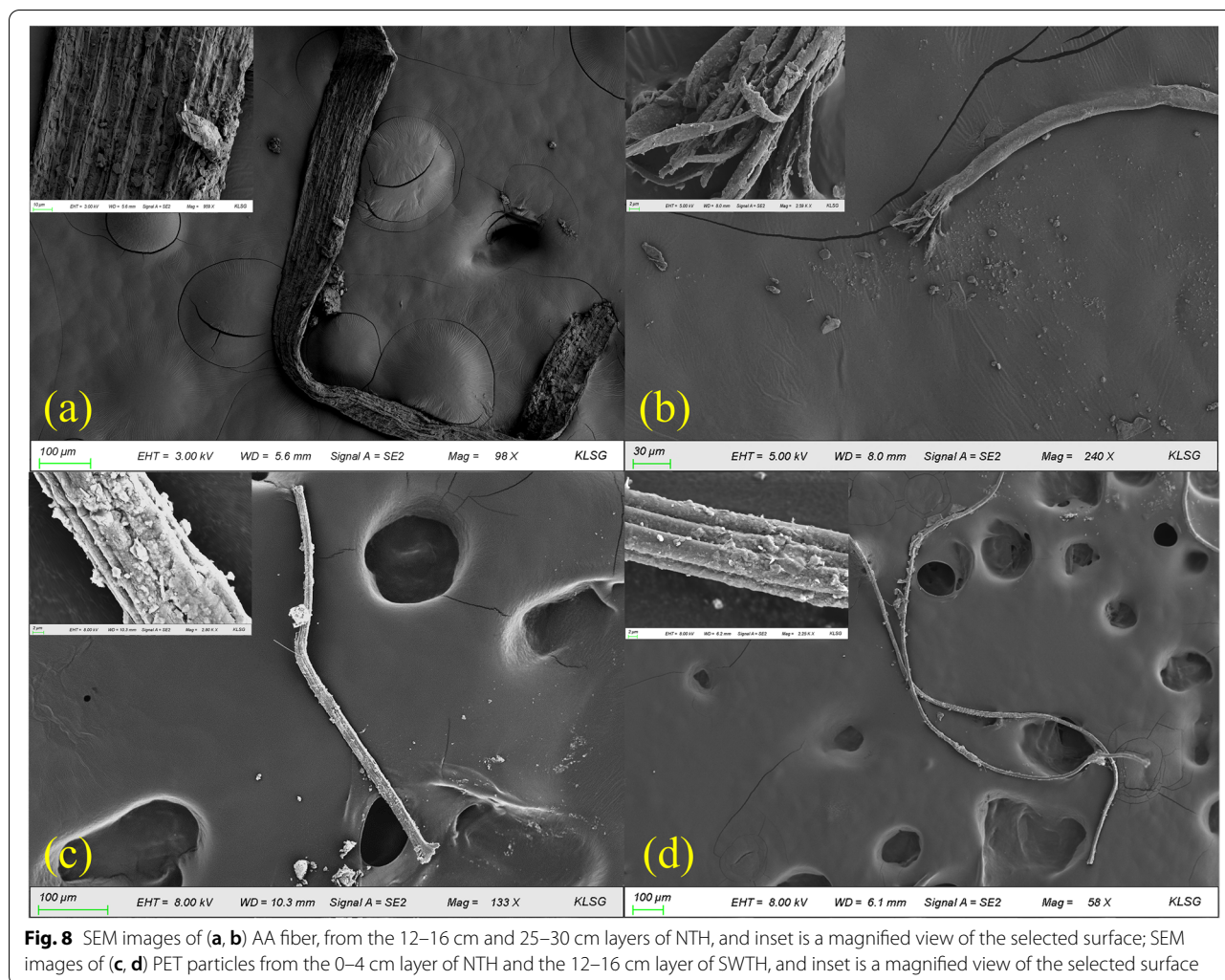


Fig. 7 Raman spectra of the collected microplastic samples (in blue) and their Raman reference library matches (in black). Representative spectra of typical microplastics are corresponding to (a) PET, (b) PP, and (c) HDPE

common composition of fibers in lake sediment [18, 33]. The main source of PET and PA fibers is fishing net and clothes, respectively [2, 30], both fibers have been detected frequently in residential and fishing areas [31]. Therefore, the high abundance of fibers in the sediment may be mainly originated from fishing activities around the Taihu. Other composition of microplastics (HDPE and AA) observed in this study also implied that there was severe household pollution near the sampling sites (Fig. 9) [35]. Furthermore, tributaries were reported as an important pathway for microplastics to enter lakes [31], such as the Lake Taihu [14].

White was the most common color among all of the microplastics detected in this study (Fig. 3; Table S1), which may be caused by the long-term decomposition in the lake and the effects of degradation during the experimental procedures [11]. White also accounted for the

largest proportion of microplastic fibers from the sediment at both sites, its amount increased with the depth at NTH (Fig. 4). Film and fragments were mainly in white color (Table S1), and they were more susceptible to decomposition into small-sized particles than fibers [36]. As a result, the pigments on the film and fragments might be easier to degrade due to their unstable composition [36]. Blue also accounted for a high abundance in the detected microplastics from the sites NTH and SWTH. The majority of the blue microplastics were fibers, which were detected in all layers of the sediment (Table S1). The blue pigment was generally identified as indigo, which is one of the common dyes used in textile industry [31]. Recent studies have shown that indigo was commonly used in the fibers of blue jeans and were widely distributed in the lake environment. The indigo fibers in the samples may come from surrounding textile mills and



household driers (Fig. S4) [31]. Black and brown (mainly fibers) were also common colors of microplastics, and they were distributed in various layers of the sediment from NTH and SWTH (Table S1). There were relatively few red and other colors (such as green and pink) observed, and their shapes were mainly fibers and pellets (Table S1).

In the sediment of site NTH, the amounts of small-sized (< 250 μm) microplastics in the 0–25 cm layers increased over depths (Fig. 5a), which agrees with some of previous studies [15, 37]. For instances, Turner et al. [15] have reported that the amounts of microplastics with size < 500 μm are increased with the growing depth in the sediment (0–25 cm) of an urban pond in North London. Another study on the sediment of Haihe River in China also showed that the abundance of the small microplastics (50–200 μm) would increase over depths (0–40 cm) [37]. Nevertheless, there was no consistent trend in the abundance of the smallest microplastics in

the 25–50 cm layers in this study (Fig. 5a). The degradation of microplastics may become slower under anaerobic and non-light conditions in the deep sediment, since the availability of oxygen and ultraviolet radiation are the most important factors for microplastic degradation [10, 36]. The abundance of small microplastics (< 250 μm) shared a similar trend in the sediment at SWTH (Fig. 5b). Microplastics with the size classes of 250–500 and 1000–5000 μm also accounted for a large proportion in the sediment of sites NTH and SWTH (Fig. 5). Those microplastics were mainly film and fibers (Fig. 4; Fig. S5).

4.3 Relationship between microplastics distribution and their sources

The microplastic distribution in the sediment of NTH and SWTH may be influenced by urbanization and the presence of industries from the surrounding area [4]. The result in this study showed that there was high

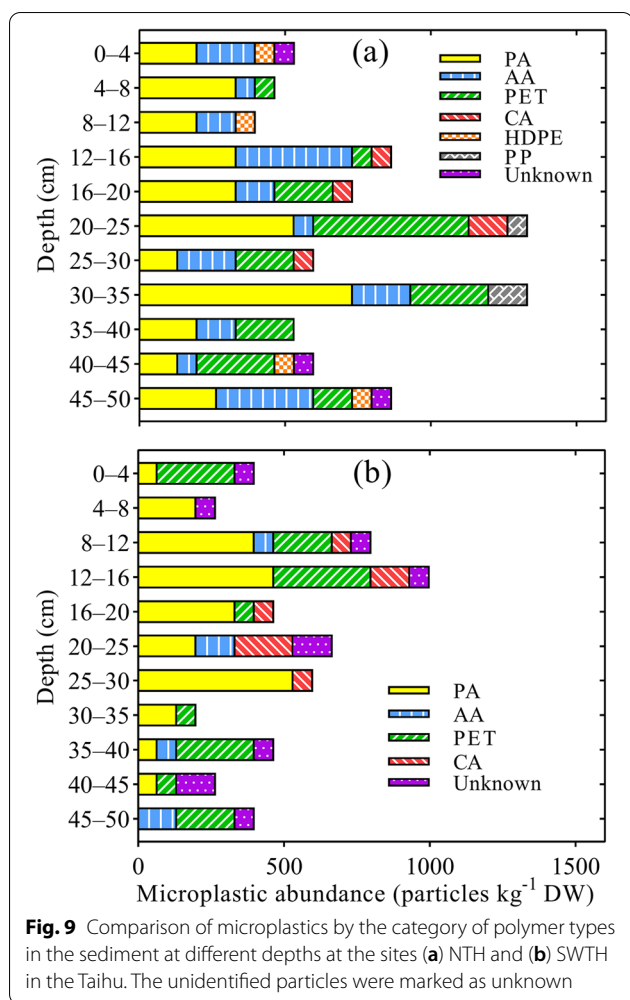


Fig. 9 Comparison of microplastics by the category of polymer types in the sediment at different depths at the sites (a) NTH and (b) SWTH in the Taihu. The unidentified particles were marked as unknown

abundance of fibers at the sites NTH and SWTH (Fig. 3). This may be due to the fact that there have been many textile industries near Meiliang Bay in the North and Southwest Taihu areas [38]. In particular, near the site SWTH, the textile industry has become one of the three main industries of the Changxing town since 1960s (Figs. S6 and S7) [38, 39].

At the site NTH, high abundance of microplastics were detected in the layers of 16–25 and 30–35 cm, while large storage of microplastics were found at the depths of 8–16 and 20–30 cm at the SWTH. This phenomenon may be attributed to the variation of deposition rates at the sites NTH and SWTH. A deposition rate in the sediment near NTH can be calculated (approximately 3.3 mm y^{-1}), according to a study by Wu et al. [27] and the dating determination results in this study (Fig. 2b). Compared to the site NTH, the highest abundance of clay minerals in the sediment of SWTH was in the shallower layers, which implied lower deposition rate of the sediment at SWTH (Fig. S8). The 16–25 cm layers with

large amounts of microplastic fibers, may be corresponding to the period of the rapid development of the fishery from 1950 to 1970s, according to the deposition rate calculated from the sediment of NTH (Fig. 3a) [39]. Due to the lower deposition rate, the 8–16 cm layers may match with the development of fishery from 1960 to 1990s near the North Taihu [33, 38]. Compared to NTH, the total abundance of film and fragments in the sediment of SWTH was apparently lower (Fig. 3). Recent study suggested that film and fragments are mainly from agricultural watersheds and plastic bottles, respectively [1]. This may be owing to larger agricultural regions in the North Taihu (Fig. S7) [33]. Therefore, the microplastic distribution at sites were closely related to the history of anthropogenic activities near the sites.

5 Conclusions

The vertical distribution and composition of microplastics at the sites NTH and SWTH in the Taihu were revealed. The results showed that there was high abundance of microplastics at both sites, and microplastics were found even in the layers of 40–50 cm. This indicated that the microplastic abundance may be considerably underestimated, if only the data of surface samples was taken into account. The sizes, colors and types of microplastics at both sites varied clearly, and the types and colors of microplastics in the sediment at the site NTH were considerably richer than that at SWTH. Fibers and white were the most abundant microplastics in the sediment at all of the sampled depths at both sites. Influenced by the anthropogenic activities from the surrounding area, the fibers and film may be originated from nearby textile and household, respectively, while the high abundance of PA discovered may be due to the development of fishery. The results provided a valuable reference for the microplastics in the sediment profiles of the Lake Taihu.

Supplementary Information

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Additional file 1: Fig. S1. Photographs of the laminar structure of the sediment with the buried depth of 91.3 cm from the Lake Taihu. **Fig. S2.** Photographs and Raman spectra of microplastics collected from the samplingsites. Photos were taken using Raman spectroscopy, the photos are corresponding to (a) polyamide (PA), (b) acrylic acid (AA), and the scale bar is 50 μm . Ramanspectra of the collected sample particles (in blue) matched with their Ramanreference library = (in black). Representative spectra of typical microplasticsare corresponding to (c) PA, (d) AA. **Fig. S3.** Photographs of microplastics collected from the sampling sites. Photoswere taken using SEM, the photos are corresponding to (a) AA, (b) celluloseacetate, and (c) PA. **Fig. S4.** almage of Raman spectroscopy (scale bar is 50 μm) and (b) Raman spectra of indigo dye from 12–16 cm layer in the North (NTH) of Lake Taihu. Raman spectraof the dye (in blue) matched

with their Raman reference library = (in black). **Fig. S5.** Photographs of typical microplastics collected from the sampling sites. Photos were taken using stereo microscope, the photos are corresponding to (a) fiber, (b) fragment, (c) film, and (d) pellet, the scale bar is 250 μm . Fig. S6 The geographical map around Changxing Town from Google Map. There are many textile industries (red triangle) in the economic development zone. Fig. S7 The geographical map around Meiliang Bay from Google Map. There are many industrial (red triangle), agricultural (yellow triangle) and residential area regions (blue triangle). Fig. S8 (a) Image of the abundance of clay minerals in the sediment of site NTH and (b) Image of the abundance of clay minerals in the sediment from Southwest (SWTH) of Lake Taihu. Table S1. Correspondence between shapes of microplastics and their colors.

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Authors' contributions

Yinan Huang provided data curation, formal analysis, methodology, and writing—original draft, Jiajia Fan provided conceptualization, resources, supervision, writing—review & editing. Huan Liu provided data curation, methodology, and investigation, Xiancai Lu provided conceptualization, funding acquisition, project administration, and supervision. All authors read and approved the final manuscript.

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Availability of data and materials

All data generated or analyzed during this study are appear in the submitted article.

Declarations

Competing interests

The authors declare they have no competing interests.

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