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Smallholder vegetable farming produces more soil microplastics pollution than large-scale farming☆

Yaqiong Hao [a,b], Haijun Sun [c], Xiaoping Zeng [d], Gangqiang Dong [e], Herbert J. Kronzucker [f], Ju Min [a,*], Changlei Xia [g], Su Shiung Lam [g,h], Weiming Shi [a,b]

[a] State Key Laboratory of Soil and Sustainable Agriculture, Changshu National Agro-Ecosystem Observation and Research Station, Institute of Soil Science, Chinese Academy of Sciences, Nanjing, 210008, China
[b] University of Chinese Academy of Sciences, Beijing, 100049, China
[c] Co-Innovation Center for Sustainable Forestry in Southern China, College of Forestry, Nanjing Forestry University, Nanjing, 210037, China
[d] Jiangsu Provincial Agricultural Technology Extension Station, Nanjing, 210036, China
[e] Amway (China) Botanical R&D Center, Wuxi, 214115, China
[f] School of BioSciences, The University of Melbourne, Parkville, VIC, 3010, Australia
[g] Jiangsu Co-Innovation Center of Efficient Processing and Utilization of Forest Resources, International Innovation Center for Forest Chemicals and Materials, College of Materials Science and Engineering, Nanjing Forestry University, Nanjing, 210037, China
[h] Higher Institution Centre of Excellence (HICoE), Institute of Tropical Aquaculture and Fisheries (AKUATROP), University Malaysia Terengganu, 21030, Kuala Nerus, Terengganu, Malaysia

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ABSTRACT

Microplastics (MPs) accumulation in farmland has attracted global concern. Smallholder farming is the dominant type in China's agriculture. Compared with large-scale farming, smallholder farming is not constrained by restrictive environmental policies and public awareness about pollution. Consequently, the degree to which smallholder farming is associated with MP pollution in soils is largely unknown. Here, we collected soil samples from both smallholder and large-scale vegetable production systems to determine the distribution and characteristics of MPs. MP abundance in vegetable soils was 147.2–2040.4 MP kg^{-1} (averaged with 500.8 MP kg^{-1}). Soil MP abundance under smallholder cultivation (730.9 MP kg^{-1}) was twice that found under large-scale cultivation (370.7 MP kg^{-1}). MP particle sizes in smallholder and large-scale farming were similar, and were mainly <1 mm. There were also differences in MP characteristics between the two types of vegetable soils: fragments (60%) and fibers (34%) were dominant under smallholder cultivation, while fragments (42%), fibers (42%), and films (11%) were dominant under large-scale cultivation. We observed a significant difference in the abundance of fragments and films under smallholder versus large-scale cultivation; the main components of MPs under smallholder cultivation were PP (34%), PE (28%), and PE-PP (10%), while these were PE (29%), PP (16%), PET (16%), and PE-PP (13%) under large-scale cultivation. By identifying the shape and composition of microplastics, it can be inferred that agricultural films were not the main MP pollution source in vegetable soil. We show that smallholder farming produces more microplastics pollution than large-scale farming in vegetable soil.

1. Introduction

Microplastics (MPs), refer to plastic fibers, fragments, and particles with a particle size of 0.001–5 mm (Li et al., 2020). Research on MPs was initially conducted mostly in aquatic environments, and, in particular, marine systems, and was gradually expanded to soil environments (Rochman, 2018), including soils of agro-ecosystems. Sludge application, irrigation water, organic fertilizers, agricultural plastic mulch films, surface runoff, atmospheric deposition, plastic wastes have all been suggested as important sources of soil MPs (Yu et al., 2021). The small size, yet large number and wide distribution, of MPs can readily lead to accumulation in soil organisms, threatening their growth and

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* Corresponding author.
E-mail address: jmin@issas.ac.cn (J. Min).

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reproduction (Dissanayake et al., 2022; Wu et al., 2022). Moreover, MPs can accumulate in the food chain, potentially harming soil biota and even entire ecosystems, and they can do so at varying nutrient levels (Rillig, 2012; Selonen et al., 2020). In addition, MPs can become part of surface runoff into rivers and lakes and cause water pollution (Rehm et al., 2021). Vertical migration of MPs also poses a potential threat to groundwater (Xu et al., 2019). Recently, the wide distribution of MPs in soils of agro-ecosystems has attracted increased attention (Okeke et al., 2022). Most of these studies have focused on cereal crops such as rice and wheat, while much less is known about vegetable crops and the soils on which they are cultivated (Chen et al., 2020).

Countries such as the United States and countries of the European Union with developed industries and rich arable land resources have realized large-scale agriculture with a high degree of mechanization and agricultural productivity, while many developing countries are still dominated by smallholder farming (Lv et al., 2019). Smallholder farming, which takes the farmer family as a unit, typically utilizes areas smaller than 2 ha (Lv et al., 2019; Ren et al., 2021). Chinese vegetable cultivation is dominated by smallholder farming, and the area of cultivation of more than 80% of farmers occupies less than 0.56 ha (Yu et al., 2022). Compared with large-scale farming (usually >20 ha), smallholder farming is not constrained by general environmental policies but can contribute significantly to agricultural pollution (Li et al., 2017). According to Ren et al. (2021), due to a lack of fixed inputs, smallholder farming frequently leads to over-fertilization. Li et al. (2021) found that smallholder farming uses mulch films to a lesser extent, but that such films are more widely distributed and more scattered, resulting in management difficulties and in generally lower recovery rates of mulch films. Plastic mulch has also been reported as one of the sources of MP pollution in farmland soil (Li et al., 2022). In addition, long-term application of organic fertilizer is an important source of MPs in soil systems (Zhang et al., 2022b). Therefore, different planting scales may affect both abundance and characteristics of soil MPs in vegetable production systems.

The degree of MP pollution in vegetable soil varies greatly among sites. Yu et al. (2021) found that there was no difference in the abundance of soil MPs in a greenhouse vegetable field (1443 MP kg^{-1}) and an open vegetable field (1860 MP kg^{-1}). As reported in a greenhouse vegetable soil in suburban Shanghai, a higher abundance of MPs was found in shallow soil (0–3 cm) than in deep soil (3–6 cm) (Liu et al., 2018). In suburbs of Wuhan, soil MP pollution in vegetable fields near suburban roads was shown to be 1.8 times that in the adjacent residential areas (Chen et al., 2020). However, it is unclear whether typical Chinese smallholder farming increases the accumulation of MPs in soils compared with large-scale farming.

The regional hydrology and soil conditions along Taihu Lake are highly suited to vegetable cultivation, and it is therefore an important vegetable production base in China (Wang et al., 2019; Min et al., 2021). Compared with cereal cultivation, vegetable planting systems contribute significantly to soil MP pollution due to a high multiple-cropping index and large input of agricultural resources (fertilizer, agricultural films). It has been reported that soil MPs may enter rivers and lakes with runoff, and finally reach the ocean (Rehm et al., 2021). Zhang et al. (2021) found that there were high levels of MPs in Taihu lake water, sediments, and surrounding rivers. Whether MP pollution plays a significant role in vegetable fields along Taihu Lake and whether it contributes to MP pollution of waterbodies is unknown.

Therefore, we selected vegetable soil along Taihu Lake to determine the occurrence and distribution of soil MPs. The particular objectives of the current study were: 1) to analyze the effect of different planting scales on abundance and characteristics (size, color, shape, composition) of soil MPs in vegetable production systems; and 2) to clarify the sources and differences of soil MPs under smallholder and large-scale farming. Our study provides important data support and a new basis for understanding and controlling MP pollution and for developing superior, more environmentally sustainable agricultural practices.

2. Materials and methods

2.1. Investigation area and sample collection

The Taihu Lake area (119°8′-121°23 ‘N, 30°15′-32°4′E) is located at the center of the Yangtze River Delta, including four prefecture-level units in Suzhou, Wuxi, Huzhou, and Changzhou (Fig. 1). The region is dominated by plains and has a typical subtropical monsoon climate with an annual rainfall amount of 1177 mm that concentrated in summer, and abundant light and water resources, highly suited to vegetable cultivation (Wang et al., 2021b).

Based on the recommendation of Jiangsu Provincial Agricultural Technology Extension Station, well-known and representative local agricultural enterprises or cooperatives were selected as the sampling points of large-scale vegetable fields (>20 ha), and the vegetable fields planted by farmer families (<2 ha) were selected as the smallholder sampling points in November 2021. The spatial distribution of the sampling regions is shown in Fig. 1. Each area has its specific characteristics, in terms of vegetable types, continuity of cropping years, mulch types, fertilizer types, irrigation regimes, and irrigation water (Table S1). All these factors are expected to lead to spatial variance in soils MP pollution levels of the various regions.

In each selected sampling area, six sub-sampling points (1 m × 1 m) were randomly selected, and 300 g of fresh soil (3 sub-sub-sampling points were randomly selected, and approximately 100 g of fresh soil was collected at each sampling point with a stainless-steel drill) was dug using a stainless-steel drill, 0–10 cm from each sub-sampled surface. The six sub-samples were collected in aluminum boxes and mixed, then brought back to the lab. Totally, 36 soil samples were collected. We spread out the soil samples in a clean and plastic-free room to air-dry and then stored the samples in aluminum boxes following sifting through a 5-mm mesh screen for subsequent separation and identification of MPs in soil samples.

2.2. MPs extraction and observation

We used a continuous flow-air flotation separation device as described in Dai et al. (2018) and Zhou et al. (2018) to separate the MPs from soil samples under room temperature, put 20.0 g of air-dried and sieved soil into a 500-mL small beaker, and ultrasonically dispersed (120 w) it with 200 mL sodium hexametaphosphate solution (0.5 mol L^{-1}) for 20 min, and then put the small beaker into a 2-L large beaker with a density of 1.2 g cm^{-3} saturated sodium chloride solution, and injected air flotation (1.0 L min^{-1}) at the bottom of the small beaker. The overflow liquid containing MPs and other low-density substances was filtered on a vibrating screen (pore diameter: 20 μm). The sieve material was washed into a conical flask containing hydrogen peroxide (30%, V/V) and placed into a constant-temperature shock chamber (50 °C, 180 r/min) for 48 h, to remove organic material. Finally, the mixture in the conical flask was filtered with a 10-μm glass fiber membrane, which was stored in the sample box at room temperature. Each sampling was repeated three times. The material on the filter membrane was observed and identified using a stereoscopic microscope (Olympus, SZX16), and the minimum observable particle size was around 20 μm. The quantity, shape, and size as well as the color of MPs observed on each filter membrane were recorded.

2.3. MPs identification

109 representative suspected MPs were selected, and selected MPs were placed on a slide covered with aluminum foil; with aluminum foil as the base, the Raman spectrum is very stable and will not cause any interference to the characteristic peaks of MPs (Sato Berru et al., 2004). Therefore, a Raman spectrometer (Thermo Fisher Scientific, DXR2, USA) was used for qualitative analysis, the Raman characteristic spectra of MPs were collected in a range of 50–3500 cm^{-1}, and the incident laser

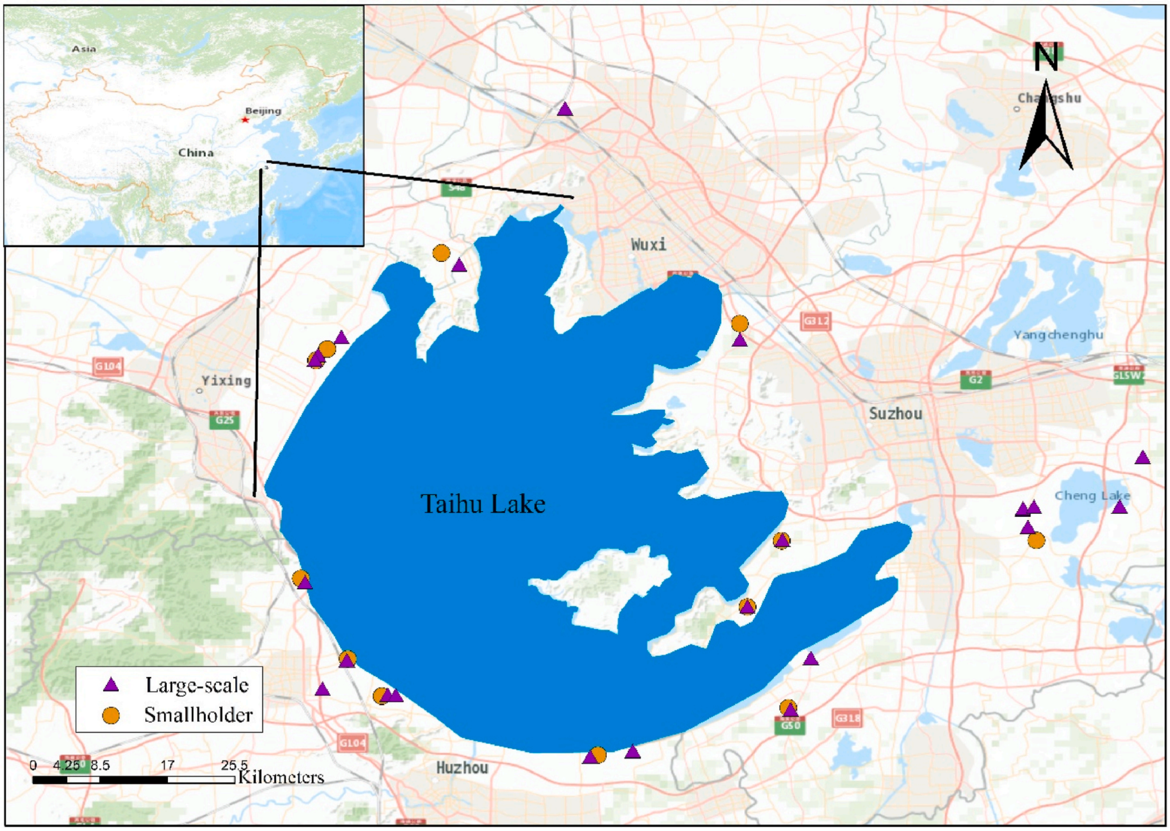

Fig. 1. Location of sampling sites of smallholder and large-scale vegetable farm operations along Taihu Lake (The background map is derived from ArcGIS Online Maps).

wavelength was 780 nm. KnowItAll software was used to smooth and correct the Raman spectrum, and the spectrum was then compared with the spectrum library in KnowItAll software (KnowItAll Raman Spectral Library), with a threshold value of >60% as the similarity cutoff to identify the chemical composition of particles.

2.4. Quality control

During the experiment, adequate precautions were taken to avoid the possibility of sample contamination. Distilled water was used to rinse all sampling instruments (stainless steel shovel, stainless steel mesh screen) before use, to avoid cross-contamination of soil samples. All glassware (glass beakers, Erlenmeyer flasks, petri dishes, and filter devices.) was rinsed with distilled water and dried in a constant-temperature blast drying oven (60 °C) prior to the experiment. During the experiment, a cotton lab coat, mask and gloves (nitrile) were worn, and the glassware was covered with aluminum foil to avoid potential contamination. The blank experiment was repeated three times during the experiment. Blank samples were MP-free distilled water and were run in parallel with the laboratory samples.

2.5. Data statistic and analysis

The unit for MPs abundance used was "MPs kg^{-1}", representing the number of MPs recorded per kilogram of fresh soil. All data were analyzed using SPSS 26.0 and Microsoft Excel 2016. One-way ANOVA was used to determine the differences in MPs abundance and characteristics (size, color, shape, composition) among smallholder and large-scale farming soils. The data were tested for normal distribution and homogeneity of variance before variance analyses were performed. Non-parametric tests were performed if the assumptions of parametric tests were not fulfilled (post-hoc Mann-Whitney *U* test). Figures were constructed using Origin 2019 and Microsoft Excel 2016, and ArcGIS 10.8 software was used to construct sampling point maps.

3. Results

3.1. 1 abundance and characteristics of MPs under smallholder and large-scale farming

3.1.1. Abundance of MPs under smallholder and large-scale farming

Non-parametric tests determined a significant ($P < 0.01$) difference in the MP abundance from soils subjected to smallholder versus large-scale vegetable farming (Fig. 2). MP abundance in soils from large-scale farms was within 147–895 MP kg^{-1} (with an average of 371 ± 161 MP kg^{-1}), while MP abundance in soils from smallholder vegetable farms ranged from 235 to 2024 MP kg^{-1} (with an average of 731 ± 558 MP kg^{-1}). Thus, on average, the abundance of soil MPs under smallholder cultivation was approx. Two-fold higher than that under large-scale cultivation.

3.1.2. Characteristics of MPs under smallholder and large-scale farming

According to the maximum length of the MPs discovered, MPs were classified into the following five grades: <0.3 mm, 0.3–0.6 mm, 0.6–1 mm, 1–3 mm, 3–5 mm, and >5 mm. The size composition of MPs in soils under smallholder farms was similar to that under large-scale farms. MPs <1 mm occupied the highest proportion, with 72% in smallholder cultivation and 65% in large-scale cultivation. The proportion of MP abundance decreased with increasing MP size (Fig. 3a): 1–3 mm (23%), followed by 3–5 mm (4%), and >5 mm (2%) in smallholder cultivation, and 1–3 mm (24%), followed by 3–5 mm (8%), and >5 mm (3%) in large-scale cultivation. Analysis of variance showed that smallholder farming had a significantly lower proportion of the 3–5 mm size class than large-scale farming ($P = 0.019$).

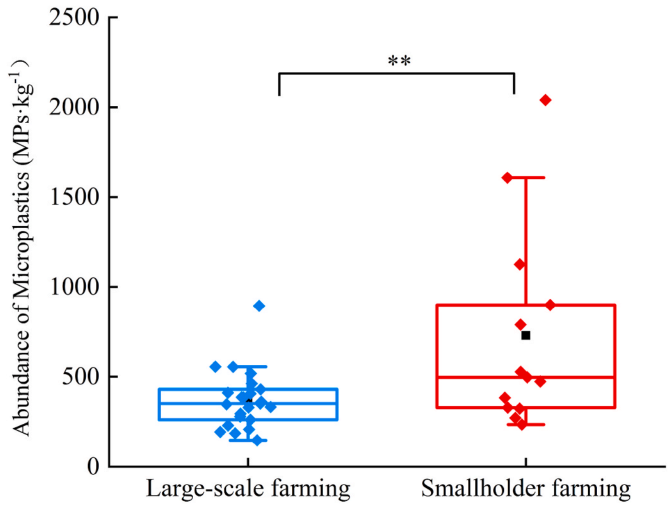

Fig. 2. Average MP abundance determined from soils of large-scale and smallholder vegetable farms. Boxes represent the 25th and 75th percentiles, central lines indicate median values, and black dots represent the average.

Five kinds of shapes, including fiber, fragment, film, particle, and others (sponge, foam), were determined in the current investigation. The morphology of MPs in soils of both smallholder and large-scale farms was dominated by fragments and fibers. Significant differences in the abundance of fragments and film between smallholder and large-scale farming were observed. The proportion of fragments in soils under smallholder operations (60%) was significantly higher than those under large-scale operations (42%) (P = 0.018), while it was lower than that in large-scale operations for film (2% vs 11%) (P = 0.005). The proportions of other shapes were not statistically different between smallholder and large-scale farming (Fig. 3b).

MPs displayed black, white, transparent, blue, green, red, and seven other colors. The leading colors of MPs determined from large-scale cultivation were black (31%) and blue (26%), while, under smallholder cultivation, these were green (32%) and blue (22%). Although the color composition was different, non-parametric tests revealed a significant ($P < 0.05$) difference only in black-color MPs between smallholder and large-scale vegetable farming in Fig. 3c.

According to the standard spectrum library in Raman spectroscopy, ten types of plastics were identified from the vegetable soils, and they were polypropylene (PP), polyethylene (PE), poly(ethene-*co*-ethylene) (PE-PP), polyethylene terephthalate (PET), polyamide (PA), polyacrylonitrile (PAN), polystyrene (PS), ethylene/vinyl acetate (EVA), polyvinylchloride (PVC) and polyvinyl alcohol (PVA). Raman spectra of the main MP polymer types are shown in Fig. S3. The main MPs in large-scale cultivation were PE, PP, and PET, with 29%, 16%, and 13%, respectively. However, the dominant MP types were PP and PE in smallholder cultivation, with 34% and 28%, respectively (Fig. 3d). The proportion of PP in smallholder cultivation (34%) was significantly higher than in large-scale cultivation (16%) (P = 0.045), while the proportion of PET in large-scale cultivation (16%) was significantly higher than in smallholder cultivation (9%) (P = 0.043). Overall, no significant difference existed in the proportion of other types of MPs (Fig. 3d).

3.2. 2 abundance and characteristics of soil MPs

3.2.1. MP abundance

We found that MP pollution was widespread in the soils of vegetable fields in the area along Taihu Lake, and MPs were found at all 36 sampling points, within a range of 147.2 to 2040.4 MP kg^{-1}, and with an average value of 500.8 ± 392.4 MP kg^{-1} (Fig. S1). Soil MP abundance in

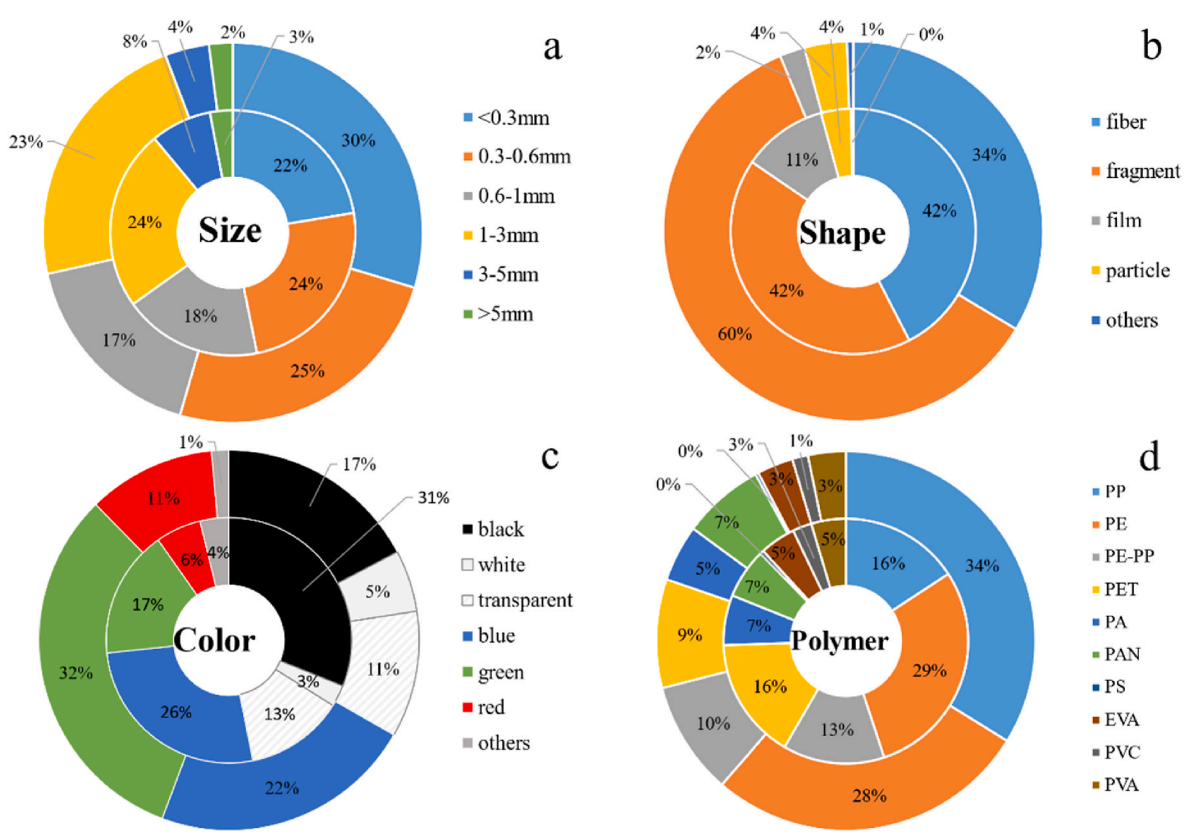

Fig. 3. The (a) Size, (b) shape, (c) color, and (d) the chemical composition distribution of soil MPs in samples (inner ring = large-scale farming, outer ring = smallholder farming). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

8% of the sampling sites was <200 MP kg^{-1}; while sampling sites with MP abundance in the 200–500 MP kg^{-1} range were the most common, accounting for 64%; MP abundance in 19% of the sampling sites was 500–1000 MP kg^{-1}; 8% of sampling sites showed abundances >1000 MP kg^{-1} (Fig. 4).

3.2.2. Characteristics of MPs

Fig. 5a shows the size distribution of soil MPs of all sampling sites. In vegetable soil, MPs <1 mm were dominant (69%), which were broken down as follows: particles <0.3 mm (26%), 0.3–0.6 mm (25%), 0.6–1 mm (18%), followed by particles in the 1–3 mm class (23%), 3–5 mm (6%), and >5 mm (2%).

As shown in Fig. S2, fragments were the dominant shape of soil MPs, with a proportion of 49%, while fibers were also frequently detected (38%), film occupied 6%, and particles accounted for only 4% (Fig. 5b).

84% of MPs in the vegetable soils analyzed were colored plastics, and the colors were mainly green (25%), blue (24%), black (24%), and transparent (12%) (Fig. 5c).

Raman spectra of the main MP polymer types are shown in Fig. S3. PE (28%) and PP (26%) were most commonly found, followed by PET (12%), PE-PP (11%), PAN (7%), PA (6%), EVA (4%), PVA (4%), PVC (2%), and PS (1%). PE and PET MPs were detected at all sampling sites (Fig. 5d).

3.3. The relationship between the characteristics of MPs

In our study, MPs of different shapes had different size distribution. The length of fragments and particles was mainly <1 mm (77% and 94%), and the length of fibers was mainly <1 mm (59%) and 1–3 mm (35%). By contrast, the size distribution of films was more variable, with >1 mm accounting for 60%, and the average size was larger than for the other three shapes (Fig. 6). The proportion of MPs <1 mm in smallholder cultivation (72%) was higher than that in large-scale cultivation (65%) (Fig. 3), which may be due to the high abundance of film in large-scale cultivation.

The composition of MPs changed with their morphology, and the composition of MPs in different morphology classes was different. The composition of fragments of MPs was mainly PP (40%), PE (39%), and PE-PP (18%). The fiber composition was rich, mainly composed of PET (29%), PAN (18%), PA (14%), PP (13%), EVA (10%), and PVA (10%), among which PA, PAN, and EVA were the most notable polymer components in fiber. The film composition was mainly PE (99%). By identifying the shape and composition of MPs (Figs. S2 and 7), it can be inferred that the source of film was mainly agricultural film. The main particle components were PET (40%), PE (38%), and PVC (14%) (Fig. 7).

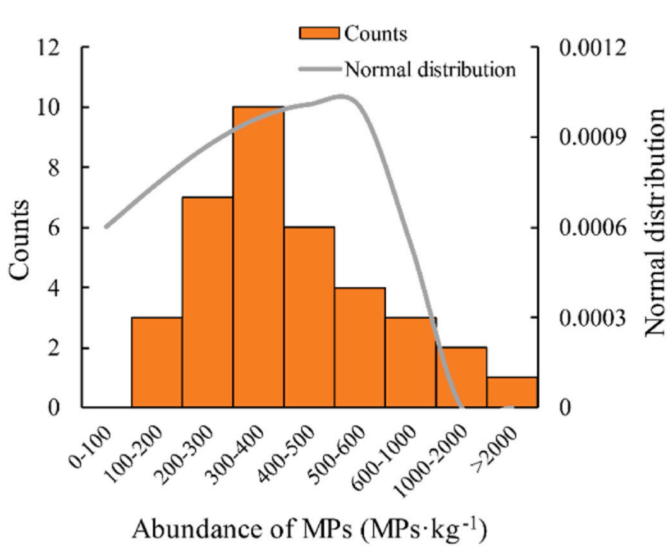

Fig. 4. Normal distribution histogram of MP abundance.

4. Discussion

4.1. Smallholder vegetable farms produce elevated soil MP pollution

Our study provides strong data support for the distribution and characteristics of soil MP pollution associated with smallholder and large-scale vegetable farming. We found significant differences in MP abundance between smallholder and large-scale farming ($P < 0.01$). Unexpectedly, we found that MP abundance under smallholder cultivation (730.9 ± 558.2 MP kg^{-1}) was twice that under large-scale cultivation. This may be the result of the combined effects of different input sources of soil MPs. Han et al. (2020) found that, compared with large-scale farming, smallholder cultivation has a higher proportion of organic fertilizer input and less application of chemical fertilizer in the Yangtze River Delta. MPs carried in organic fertilizer can be a significant source of pollution in farmland soil (Zhang et al., 2022b), which consequently can lead to heavier MP pollution of waterbodies. A large proportion of organic fertilizer is applied in smallholder farms of the Taihu Lake region. In addition, our survey (Fig. S4) shows that large-scale vegetable plots are usually in uniformly managed production parks, while smallholder vegetable plots are much less concentrated and are usually scattered along roadsides and in family courtyards. Atmospheric deposition, household garbage, and dust from road traffic can further contribute to MPs in these smallholder vegetable plots (Kole et al., 2017; Wagner et al., 2018). Due to the lack of regulatory supervision, plastic products, including bags, frequently accumulate along roadsides in such areas. Large traffic flow, strong mobility, and wide spread around the road may cause a high accumulation of MPs in adjacent soils (Chen et al., 2020). Especially road traffic dust may, therefore, seriously increase MP abundance in smallholder vegetable farm soil. In summary, smallholder farming is associated with higher MP pollution than large-scale farming, attributable to factors such as road traffic, a higher multiple-cropping index, and larger amounts of organic fertilizer used in smallholder operations.

The current study also examined basic variables at each sampling point (Table S1), such as type of vegetable, planting age, fertilizer type, irrigation water source, and irrigation method. According to the statistical analysis of the above basic information, no significant difference was found between smallholder and large-scale farming in these respects. There was, however, a significant difference between smallholder and large-scale cultivation in terms of whether covers with agricultural films were employed ($P < 0.01$). The results also suggest a significant difference in the abundance of films between smallholder and large-scale farming ($P < 0.01$) (Fig. S5); large-scale farming produced significantly higher values (40.6 MP kg^{-1}) than smallholder farming (16.2 MP kg^{-1}). Large-scale farming pays more attention to the output value of vegetables, farming intensity is higher, sheds are rarely opened for leisure activities, agricultural films are mostly reused, and covers remain for long periods (Han et al., 2020). Therefore, it is reasonable that large-scale farming should be associated with higher more film MP abundance. This result agrees with Zhang et al. (2022a), who found that the abundance of PE film in farmland was significantly higher than that in non-filmed farmland due to the thinness and brittleness of PE film. However, the overall abundance of MPs in mulched vegetable soil (377.6 MP kg^{-1}) was significantly lower than in non-mulched vegetable soil (1130.2 MP kg^{-1}). As shown in Table S2, there were no significant differences in irrigation water sources, irrigation types, fertilization types, and fertilization methods between film-covered vegetable fields and non-film-covered vegetable fields. The difference in MP abundance between the two field types may therefore be related to exogenous contamination with MPs, such as via road traffic dust, domestic waste, and atmospheric deposition (Chen et al., 2020). Film mulching may effectively block other forms of MPs from entering into the soil, thereby reducing the abundance of soil MPs in mulched

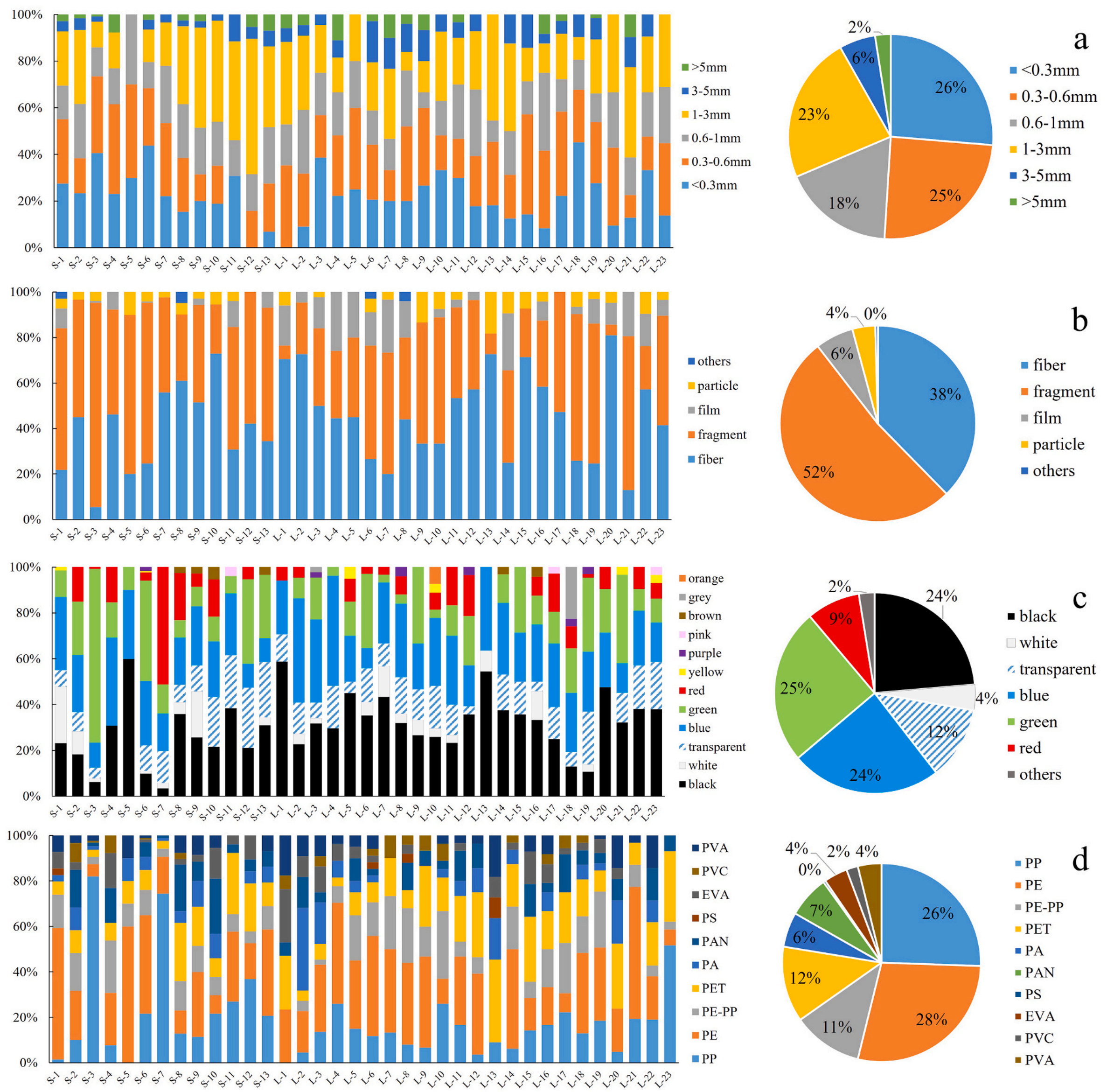

Fig. 5. Characteristics of MP size (a), shape (b), color (c), and chemical composition (d) in vegetable soils. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

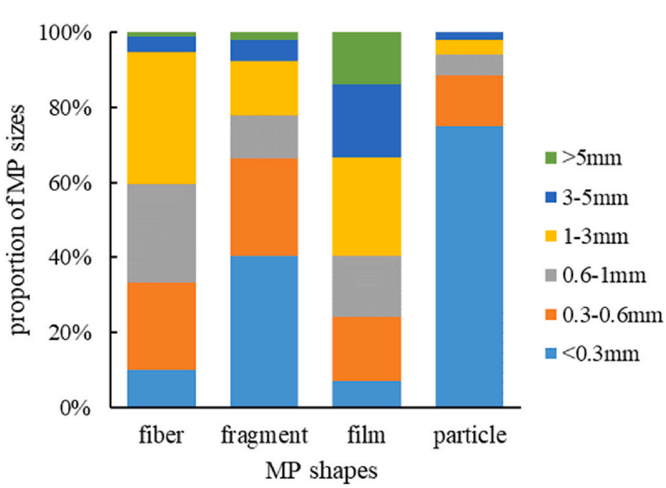

Fig. 6. Sizes of the different MP shapes.

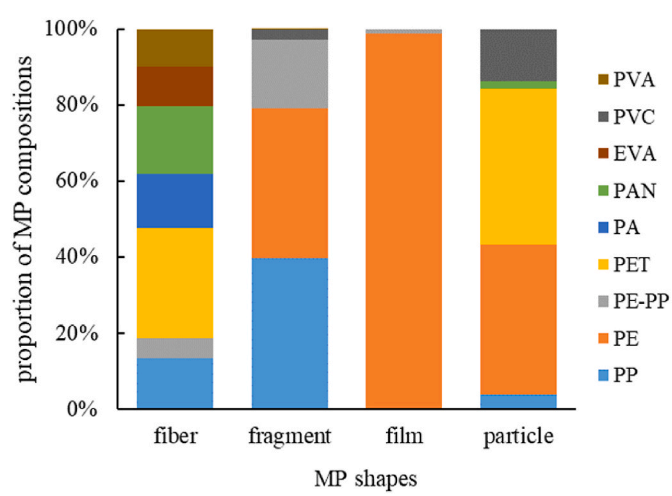

Fig. 7. Compositions of the different MP shapes.

vegetable fields. Compared with non-covered vegetable fields, covered vegetable fields showed reduced content of MPs in the forms of debris (−66.4%) and fiber (−39.4%). We infer that the differences in the abundance, shape, and type of MPs in vegetable fields covered with film and non-covered vegetable fields are related to the application of mulching film, and that long-term mulching may prevent certain MPs from entering the soil, reducing overall MP content. By contrast, Zhou et al. (2020) found that the abundance of MPs (571.2 MP kg^{-1}) in mulched farmland soil was much higher than that in non-mulched soil (262.7 MP kg^{-1}). Among the sampling points selected by Zhou et al. (2020), plastic-covered soil was mainly for planting vegetables, melons, and other fruits, while non-film-covered land was mainly planted to rice, corn, and other cereal crops. There were also significant differences in soil MP abundance found with different land use patterns (Corradini et al., 2021). Zhou et al. (2020) also found that soil MPs in farmland were mainly in the form of debris, not films. Other sources (such as irrigation water or compost) can also make important contributions to soil MP pollution. Differences in the selection of land use methods at the various sampling sites can also lead to differences. The sampling points selected in this paper were, therefore, exclusively from vegetable fields, avoiding the added complications arising from different land use methods. In addition, although mulching reduces the entry of MPs into soils, the agricultural films used also can be an important MP pollution source, an issue that can be minimized by use of biodegradable films or recyclable thick films, which can replace PE films (Mistretta et al., 2021).

4.2. The abundance and characteristics of soil MPs from vegetable production system

In this investigation, the abundance of MPs in vegetable soil ranged from 147.2 to 2040.4 MP kg^{-1}, and the mean value was 500.8 ± 392.4 MP kg^{-1}. In order to understand the MP pollution level of vegetable soils along Taihu Lake, we summarize, in Table S2, data on MP pollution levels and characteristics detected in farmland soils with different land use patterns both in China and abroad. As can be seen from Table S2, there are large varieties in the abundance of MPs in farmland soils in different areas. Compared with the results from other studies, in China, MP abundance in vegetable soils in the Taihu Region is at a moderate level. MP abundance in vegetable soils along Taihu Lake was higher than that in Shanghai (Liu et al., 2018), Jiangsu, Zhejiang (Cao et al., 2021), and Shanxi (Zhang and Liu, 2018; Liu et al., 2018), but lower than in Hubei (Chen et al., 2020; Liu et al., 2022), Shandong (Yu et al., 2021), and Qinghai (Feng et al., 2021). Compared with other countries, MP abundance in this study is high. MP abundance in vegetable soils along Taihu Lake was higher than that reported for soils in Chile (Corradini et al., 2019), Germany (Harms et al., 2021), Iran (Rezaei et al., 2019), and Mauritius (Ragoobur et al., 2021). The abundance of MPs varies across studies, and this may be related to differences in soil sample depth, planting crops, sampling location, fertilization level, mechanical disturbance, contamination source, precipitation, and MP extraction methods (Fuller and Gautam, 2016; Liu et al., 2018; Liu et al., 2022; Yang et al., 2021). For example, there was a chemical fiber factory next to the sampling site in Hubei, and this obvious source of pollution resulted in a high abundance of MPs, especially fibers (Chen et al., 2020). Agricultural film is also used in farmland in Yunnan, and sewage is used on irrigated land (Zhang et al., 2018). For this study, there was no obvious source of pollution, resulting in lower MP abundances compared to our study (Cao et al., 2021). It should also be pointed out that the flotation liquid used in this study was non-toxic NaCl solution instead of other high-density solutions (such as $CaCl_2$ solution). Due to the low density of NaCl solution, some high-density MPs may be lost during the separation process, so that the abundance of MPs may be underestimated (Wang et al., 2021a). Therefore, the MPs pollution of vegetable soil may be more significant than estimated.

MPs in farmland soil, as reported in recent studies, were analyzed statistically (Table S2). This analysis reveals that the same area subjected to different land use types (cereal crops, vegetable field, orchards and woodlands, meadows) yields different MP abundances, with MP abundance at its highest in vegetable soils, followed by soils under orchards and woodlands, and meadows, and MP abundance at a minimum with cereal crop cultivation. High intensity tillage, continuous film mulching, and fertilization in greenhouse vegetable plots resulted in increased MP abundance (Yu et al., 2021). According to Wang et al. (2022), film mulching is a direct source of MPs in soil. Continuous agricultural film mulching aggravated the accumulation of MPs in cultivated soils (Huang et al., 2020). Except for greenhouse vegetable plots, the other three land use types do not require mulching, thus eliminating the pollution by mulch MPs (Table S2). Organic fertilizer contains a large number of MPs, and this can be a large source of soil MPs in agricultural systems (Zhang et al., 2022b). Huerta Lwanga et al. (2017) has observed that the abundance of MPs in organic fertilizer applied to vegetable fields reached 129,800 MP kg^{-1}. Moreover, organic fertilizer is frequently applied to vegetable fields and orchard soils. Indeed, the application rate of organic fertilizer in vegetable fields can be almost ten times that in traditional cereal crop fields (Zhang et al., 2016). In addition, Zhang et al. (2020) found chemical fertilizers have a “start-up” effect on the decomposition of MPs. Nitrogen and phosphorus not only improve soil fertility, but can also increase the diversity of the soil microbial community and the abundance of some microorganismal groups. Some of these groups produce enzymes, in particular oxidoreductases and hydrolases, that can effectively degrade MPs (Zhang et al., 2020). The degradation of plastic produces a mass of small fragments, which contributes to soil MP abundance (Zhang et al., 2020). We found that land use methods and crop types determine the degree to which plastic mulching, tillage, and fertilizer are employed, thus affecting the abundance of MPs.

In our work, the dominant size of vegetable soil MPs was <1 mm, and the main forms of MPs were fragment and fiber, with colors of green, blue, and black. Furthermore, a large proportion of MPs were PP and PE. The results of this study are similar to those of other workers examining different soil systems (Table S2). Table S2 shows that the size of MPs in farmland soils in various regions is predominantly <1 mm, and the size of MPs is distributed exponentially, i.e., with increasing particle size, the proportion gradually decreases, which may be related to effects of ultraviolet radiation, high temperature, and mechanical wear, facilitating the breakdown of larger particles into smaller ones (Horton et al., 2017; Piehl et al., 2018). Fiber, debris, and film were the major shapes in tested soil. The distribution of MPs varies slightly with land use type. For example, the soil of greenhouse vegetable plots requires film mulch, and the content of MPs from film can be quite high (Feng et al., 2021). Fibers are thin and light and easily migrate with water. The proportion of MPs from fiber in paddy fields has been shown to be higher than in other land use types (Zhou et al., 2020). In addition, although based on limited data (Table S2), our analysis shows that, compared with China (proportion of films: 6%–81%), the abundance of films in other countries was relatively lower (usually below 10%). In China, a four-fold increase of plastic mulch use, from 319 to 1245 megatons, has been noted between 1991 and 2011, and much of this is difficult to recycle. In Spain and many eastern and south-eastern countries, more than 50% of plastic waste is estimated to be landfilled (Steinmetz et al., 2016). Slight differences in the composition of MPs with different land use patterns in different regions have also been reported (Wang et al., 2021a), but on the whole, the proportion of PE and PP MPs in farmland in each region exceeded that of other MP types. PP is an important material for the manufacture of food bags, woven bags, fishing nets, and ropes (Ding et al., 2021; Ding et al., 2020), and PE is widely used in the manufacturing of agricultural films, plastic bags, pesticide bottles, and fishing nets (Rong et al., 2021; Wang et al., 2022). These polymer types have been found in many agricultural soils, confirming that agricultural activities can lead to MPs entering soil. In addition, 84% of MPs in vegetable soil occur as colored plastics. Colored plastics usually require color masterbatches and various chemical additives during production. While improving the ease of processing and performance of plastics, they also release various harmful substances such as aromatic amines, heavy metals, and fluorescent whitening agents (Dissanayake et al., 2022; Oliviero et al., 2019; Sridharan et al., 2022). Therefore, compared with colorless plastics, colored plastics are more harmful to soil and crops.

Since agricultural soils are frequently affected by significant erosion, MPs can be transported into surrounding rivers and lakes via surface runoff (Rehm et al., 2021). Both Zhang et al. (2021) and Su et al. (2016) found a high abundance of MPs in Taihu Lake and in surrounding rivers. Compared with cereal cultivation, vegetable planting systems can have a particularly prominent contribution to soil MP pollution due to a high multiple-cropping index and large input of agricultural materials (such as fertilizer and agricultural films) (Yu et al., 2021). Yu et al. also found that, in recent years, the area around Taihu Lake that is planted to vegetables has increased significantly, while paddy fields in the area have decreased significantly (Min et al., 2020). These changes in crop cultivation around Taihu Lake are likely to have intensified soil MP pollution, thus bringing greater risks to Taihu Lake water pollution with MPs.

5. Conclusions

In the current investigation, we observed the occurrence and characteristics of MPs in smallholder and large-scale farming soils. The results suggest that the abundance of MPs in smallholder farming (730.9 MP kg^{-1}) is higher than that in large-scale farming (370.7 MP kg^{-1}). Moreover, the differences in the shape and composition of MPs between the two types of vegetable soils were significant. This may be related to the higher multiple-cropping index, a higher influence of road traffic, higher application amounts of organic fertilizer, and to the management of shed membranes in smallholder vegetable farms. MPs may have a potentially significant impact on soil health and crop quality, greater attention must be paid to smallholder farming operations, and we view it as important to promote larger-scale farming in China. In addition, although agricultural film is not the main source of MP pollution, we recommend that biodegradable films or recyclable thick films be used to replace PE films to control the input of films MPs.

Author statement

Yaqiong Hao: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing, Haijun Sun: Formal analysis, Data curation, Writing, Xiaoping Zeng: Resources, Investigation, Gangqiang Dong: Resources, Investigation, Herbert J. Kronzucker: Writing – review & editing, Ju Min*: Conceptualization, Validation, Writing, Supervision, Changlei Xia: review & editing, Su Shiung Lam: review & editing, Weiming Shi: Conceptualization, Validation, Supervision.

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.

Data availability

No data was used for the research described in the article.

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Appendix ASupplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2022.120805.

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