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Microplastics may act as a vector for potentially hazardous metals in rural soils in Xiamen, China

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Abstract

Purpose Soil represents a key reservoir for microplastics (MPs) in the terrestrial environment. Unfortunately, scientific endeavors on MP pollution in rural soils of coastal cities appear to be inadequate. The interconnection between rural soil MPs and potentially hazardous metals (PHMs) is underexplored. This work investigated the combined pollution of MPs and 8 PHMs (As, Cd, Cr, Cu, Zn, Pb, Hg, and Ni) in the rural soils of Xiamen, a typical coastal city in China.

Materials and methods Sixteen sites were selected based on different administrative areas and representative land use types in Xiamen for surface soil sampling. MP selection and identification were performed using a stereo light microscope and Senterra II Compact Raman Microscope. MPs were analyzed for elemental composition using scanning electron microscopy with energy dispersive X-ray spectroscopy. Soil properties and PHMs concentrations were measured using the relevant industrial and national standards.

Results and discussion The abundance of MPs ranged from 15 to 2222 items kg^{-1} with an average of 229 ± 523 items kg^{-1}, suggesting that the rural soils have been widely disturbed by MP contamination. The dominant shape, color, and size of MPs were fragments (55.3%) and fibers (35.8%), transparent (59.3%) and white (17.7%), and < 1 mm (64.4%), respectively. Polypropylene (67.6%) was the main polymer type, followed by polystyrene (11.0%) and polyester (9.4%). The abundance of MPs (except for the most contaminated S13) was not highly associated with PHMs contents in rural soil. The energy dispersive X-ray spectra manifested irregular distribution of Zn and Pb on the MP surfaces at site S13.

Conclusion MP pollution was widespread in rural soils in Xiamen. MPs served as the potential vector that transmitted PHMs to soils at high levels of PHMs. The rural soil MPs in Xiamen may be originated from agricultural, industrial, and human activities. This study provides insights into combined contamination of MPs and PHMs in rural soils in Xiamen, which will help formulate effective pollution abatement measures.

Keywords Microplastics · Rural · Soil · Xiamen, potentially hazardous metals

1 Introduction

Microplastics (MPs) as a global menace have invaded every corner of the planet. MP contamination has been found in a broad spectrum of environmental settings, such as freshwater (Koelmans et al. 2019), ocean (Cole et al. 2011; Pan et al. 2019), sediments (Morgado et al. 2022), soil (Wang et al. 2019), organisms (Wright et al. 2013), and atmospheric environment (Evangeliou et al. 2020). Although the majority of MP investigations have focused on the marine environment,

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marine MPs were mainly from terrestrial sources (Andrady 2011). The investigations of MPs in the soil are equally important yet often neglected (Wang et al. 2019). In response, attention should be shifted to the MP pollution on land. The negative impacts of the proliferation of MPs in the terrestrial soil ecosystems have raised public awareness. According to a recent report by the United Nations Food and Agriculture Organization (FAO), soil plastic pollution seems to be worse than that in the oceans. It is estimated that as much as 80% of marine plastic debris are originated from land (FAO 2021). MP pollution in the soil is affected by different sources of pollution in different geographical regions. MPs were introduced into the soil via multiple routes, including plastic waste disposal (Zhou et al. 2021), atmospheric deposition (Horton et al. 2017), precipitation (Bergmann et al. 2019), irrigation (Mason et al. 2016), and agricultural activities (Huang et al. 2020). In particular, the crop production and livestock sectors in the agricultural value chains are the largest users of plastic products, consuming 10 million tonnes per year collectively (FAO 2021).

MPs have been well-documented to serve as vectors for chemicals and pathogens that cause hazards to human health (Ashton et al. 2010; Engler 2012; Fisner et al. 2013; Zettler et al. 2013). Due to small particle size, higher surface area, and polarity, MPs were prone to sorb and concentrate pollutants, such as potentially hazardous metals (PHMs), thereby yielding added concerns and combined pollution. The aged MPs in the soil had a larger surface area and changed oxygen functional groups, which facilitated the interaction with PHMs (Brennecke et al. 2016; Liu et al. 2020a; Turner and Holmes 2015). MPs in conjunction with PHMs may change soil properties, metal mobility, and microbial diversity and functions, thereby affecting the soil ecosystem (Feng et al. 2022). Chlorophyll content, photosynthetic activity, and induction of reactive oxygen species in plants were affected by the co-occurrence of MPs and heavy metals (Kumar et al. 2022). Furthermore, the impacts of MPs on the bioaccumulation of PHMs in crops had been demonstrated, and results had shown that MPs promoted the bioaccumulation of heavy metals in vegetables and cause vegetable damage (Jia et al. 2022). The combined contamination of MPs and PHMs played a role in the survival of animals in the soil. Earthworms were negatively affected in soils where MPs and cadmium were both present (Zhou et al. 2020b). The intervention from MPs or complex of MPs and PHMs may adversely impact the soil flora and fauna, resulting in the potential to harm agricultural productivity, food security, and human health.

As of yet, information about the quantities of MPs entering terrestrial environments, particularly in rural soils of coastal areas, is virtually fragmentary as opposed to marine MPs. For example, such a knowledge gap in the rural areas of Xiamen, a typical coastal city in China, is prominent. The connections between MPs and PHMs in the rural soils of Xiamen remain unknown. The objectives of this study were: (1) to investigate the abundance and characteristics of MPs in rural soils of Xiamen; (2) to explore the spatial distribution patterns of MPs and PHMs (As, Cd, Cr, Cu, Zn, Pb, Hg, and Ni) in different administrative districts of Xiamen City and representative sampling sites; (3) to relate the abundance of MPs to the contents of PHMs in rural soils; and, (4) to identify potential sources of MPs. This study will assist in promoting the understanding of the *status quo* of MP pollution in rural soil in Xiamen. The findings will establish a robust basis for future studies on the combined contamination of MPs and PHMs in rural soils of coastal regions. It will also provide science-based support in developing solutions for sustainable land management and the agricultural environment into the future.

2 Material and methods

2.1 Sampling area and soil sampling

The study area is located in Xiamen, a typical coastal city. A total of 16 surface soil samples were collected in August 2021. The sampling sites were selected based on different administrative areas and representative land use types, including four administrative districts, Jimei District (JM, $n=2$), Haicang District (HC, $n=2$), Xiangan District (XA, $n=10$), and Tongan District (TA, $n=2$). There were 10 sampling sites in XA, including sewage treatment plants, drinking water sources, the area around the pig farm, forest, and farmland. The details were provided in Fig. 1 and Table S1 (Supplementary Material, SI).

At each sampling site, 5 uniform fields were sampled using a wooden shovel in a simple random pattern at a depth of 0–10 cm. The 5 sub-soil samples were thoroughly mixed as a composite sample for each site (~500 g) to ensure the representativeness of the sample, which was stored in a sealed glass jar. Only the fine soil was sampled. Rocks, grass, plant, and biological debris were excluded.

2.2 Separation and identification of MPs

An aliquot of ~150 g of wet soil samples was dried in an oven at 60 °C to a constant weight. The wet and dry weights of the samples were recorded for moisture content. The dried samples were soaked in saturated $ZnCl_2$ solution ($\rho = \sim 1.6$ g cm^{-3}). Samples with excessive organic matter were further digested using H_2O_2. Samples after density separation in the flotation medium were transferred to GF/F Whatman filters ($d=47$ mm, pore size = 0.7 μm) by vacuum filtration. Suspected MPs on the dried Whatman filters were selected with the aid of a stereo light microscope (Leica

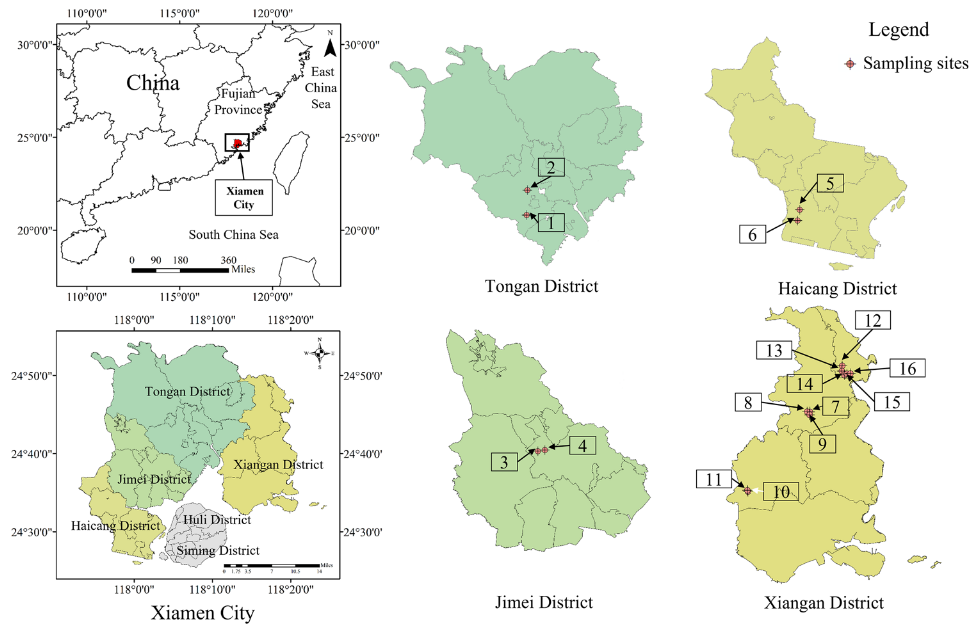

Fig. 1 Sampling sites of soil MPs in Xiamen

M205A, Germany). The number, shape, color, and size of the putative MPs at each site were recorded. The polymer composition of the suspected MPs was identified using Senterra II Compact Raman Microscope (Bruker Optics Inc., MA, U.S.A.). Then, the identified sample spectra were compared with the standard spectra by OPUS 7.5 (OPUS software Inc., San Rafael, CA) software to confirm the results.

2.3 Microscopic and SEM/EDS analysis

MPs were photographed using a Leica DFC425 charge-coupled device (CCD) camera equipped with a stereo light microscope. The MPs were ultrasonically cleaned and then air dried at room temperature. MPs were analyzed for elemental composition at selected surface microdomains by using scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM/EDS). The images of MPs were obtained by using a scanning electron microscope (ZEISS EVO-18, Oberkochen, Germany) with an operating voltage of 20 kV and a magnification of 90–2000×. Gold spray treatment on the surface of MP and the qualitative elemental composition of selected areas of the MP surface was determined by EDS (X-Max^N, Oxford Instruments, U.K.).

2.4 Measurement of soil properties and PHMs concentrations

Soil properties, including pH, organic matter, and cation exchange capacity (CEC), were measured in this study. The soil pH was determined by potentiometry (HJ 962–2018). The soil organic matter was analyzed according to the standard (NY/T 1121.6–2006). The soil CEC was determined using hexaamminecobalt trichloride solution-spectrophotometric method (HJ 889–2017). According to the Soil environmental quality-Risk control standard for soil contamination of agricultural land (GB15618-2018), As, Cd, Cr, Cu, Zn, Pb, Hg, and Ni were targeted in this study. Concentrations of Hg and As in soils were determined using atomic fluorescence spectrometry (GB/T 22105.2–2008), and graphite furnace atomic absorption spectrophotometry was used to detect concentrations of Cd and Pb in soils (GB/T 17141–1997), and flame atomic absorption spectrophotometry was adopted for measuring Cr, Cu, Zn, and Ni concentrations in soil (HJ 491–2019).

2.5 Statistical analysis

The sampling sites were mapped using ArcGIS 10.5 software and the data were analyzed using Origin 2020, ArcGIS, Excel, and OPUS 7.5. MP abundance is expressed as the number of MP particles per kilogram of the dry mass of soil (items kg^{-1}). Correlation analyses of MP abundance with soil properties and PHMs content in the soil were performed using SPSS software.

3 Results

3.1 Abundance of MPs

The abundance of soil MPs in the four administrative districts of Xiamen ranged from 15 to 2222 (items kg^{-1}), with a mean of 229 ± 523 items kg^{-1}. The smallest and largest abundance of MPs were detected in site 9 and site 13 in XA district, with 15 and 2222 items kg^{-1}, respectively. The extreme values contain a difference of more than two orders of magnitude. The MP abundance in the four districts was found to be in descending order: XA (mean abundance: 333 ± 640 items kg^{-1}) > HC (mean abundance: 83 ± 15 items kg^{-1}) > TA (mean abundance: 59 ± 15 items kg^{-1}) > JM (mean abundance: 27 ± 4 items kg^{-1}, Fig. 2). The result suggested that soils in XA district were the most contaminated by MPs. Furthermore, the MP abundances in the soil at different representative sampling sites were in the following descending order: drinking water source (2222 items kg^{-1}) > forest (207 items kg^{-1}) > farmland (184 items kg^{-1}) > the area around the pig farm (23 items kg^{-1}) > sewage treatment plant (17 items kg^{-1}) (Fig. 2). The spatial distribution of MPs in rural soils was highly heterogeneous in different regions.

3.2 Characteristics of MPs

Figure 3A delineated that five types of MP shapes, including line, fiber, fragment, granule, and film, were observed in the

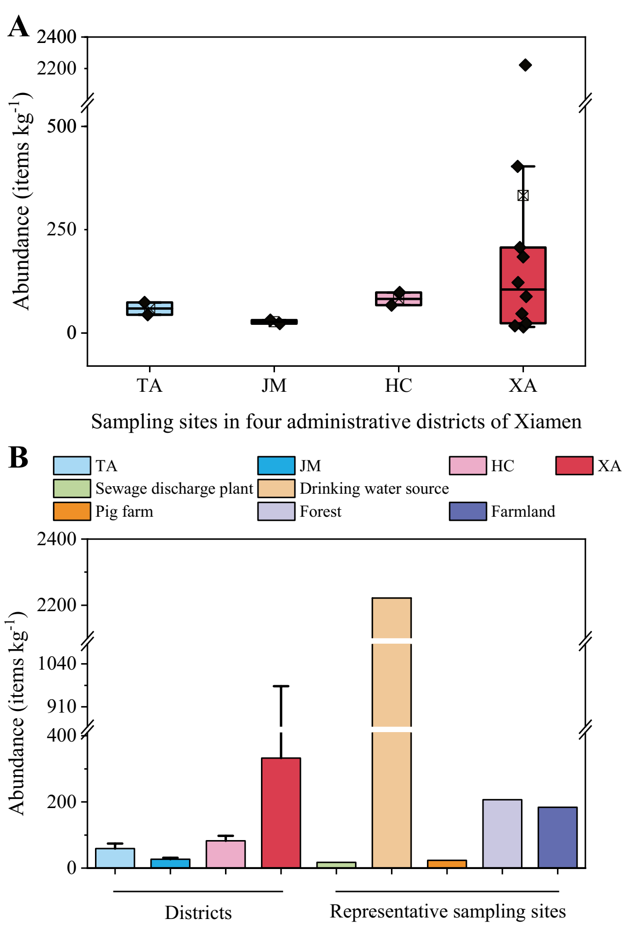

Fig. 2 The distribution of MP abundance in the soils. **A** the box plot of MP abundance. **B** the average of MP abundance in different districts and MP abundance at representative sampling sites

rural soils of Xiamen (Figs. 3A and 4). Fibers were the most prevalent in most sampling sites but were absent in the sewage treatment plant (S12). Lines were present in TA district, XA district, sewage treatment plant, drinking water source, forest, and farmland, while fragments were found in TA district, XA district, drinking water source, forest, and farmland. In addition, films were present in XA district, drinking water source, and farmland. The granules were exclusively present in XA district and drinking water source. Notably, only one shape of MPs was detected in JM district (fiber), HC district (fiber), sewage treatment plant (line), and the area around the pig farm (fiber). The five shapes of MPs were not uniformly present at the different sampling sites, suggesting various sources of MPs. Overall, the five shapes of MPs in rural soils from 16 sampling sites in Xiamen were dominated by fragment (55.3%) and fiber (35.8%), followed by line (7.6%), granule (0.7%), and film (0.7%).

Eight different colors of MPs were observed in this study, namely, white, yellow, red, blue, black, green, clear, and purple (Figs. 3B and 4). Of these, transparent (absent in sewage treatment plants) and white (not detected around sewage sites and pig farm) MPs were dominant. The results showed a predominance of transparent (59.3%), white (17.7%), and red (11.9%) MPs in terms of quantity. There were discrepancies in the size distribution of MPs in different soils. Results from sampling sites in TA district, HC district, XA district, drinking water source, forest, and farmland showed that MPs were detected in the size range of 0.1–5 mm, while results from the sewage treatment plant and drinking water source showed that MPs were only observed in the range of 1–2.5 mm and 2.5–5 mm, respectively (Fig. 3C). The size range of MPs accounted for the largest proportion of 0.1–0.5 mm (39.6%), and those smaller than 1 mm accounted for 64.4%. However, MPs in the larger size range (> 2.5 mm) only accounted for 10.1% of the total.

Figure 3D indicated that polyethylene (PE), polypropylene (PP), polyethylene-polypropylene (PE-PP), polyethylene terephthalate (PET), polystyrene (PS), and polyethersulfone (PES) were detected in soil at the sampling sites of this study. PES was observed in all sites except the sewage treatment plant, while all six types of polymers were found in XA district. The results of the type of polymer detected for MPs in the soil showed that PP (67.6%) dominated the soil, followed by PS (11.0%), PES (9.4%), PE-PP (5.4%), PE (4.7%) and PET (2.0%).

Figures 4 and S1 showed the morphology of the MPs taken by the CCD camera and SEM, respectively (Fig. 5). Most MPs were either transparent or white, and the rest MPs were red, green, and blue. Note that the color of some MPs had faded and turned yellow. The surfaces of line-like MPs were shown with pits, flakes, and rough texture. There were bends, deformities, roughness, and unevenness in the fibers,

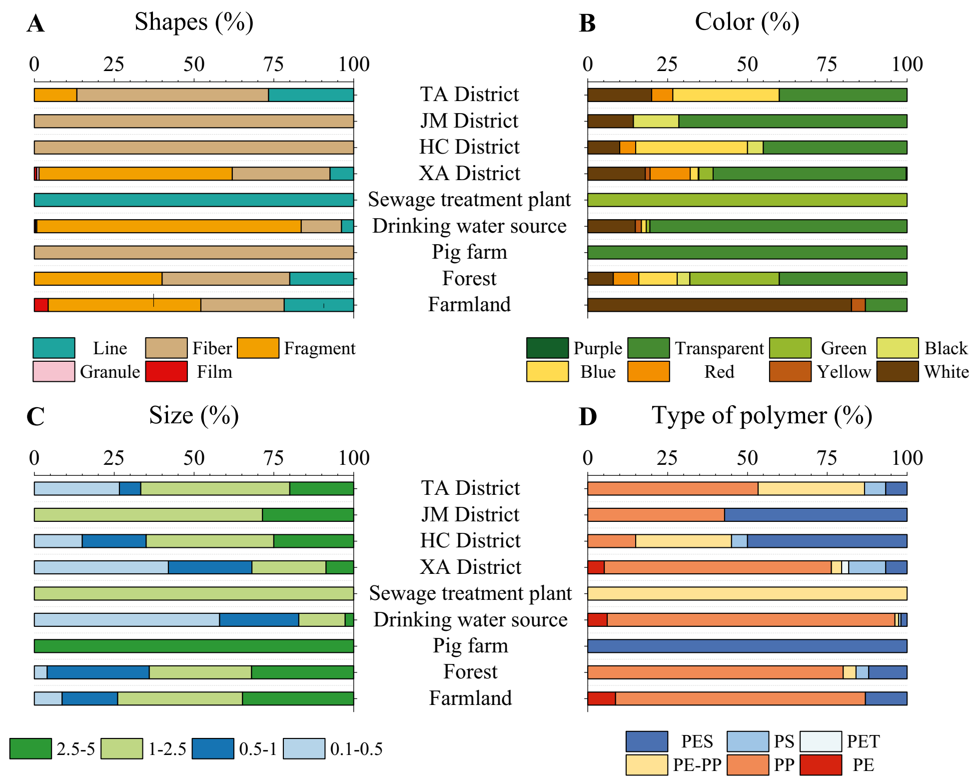

Fig. 3 MP shapes (**A**), colors (**B**), sizes (**C**), and types of polymer (**D**) in rural soils

suggesting that environmental aging processes compromised the integrity of fibers. The particles seemed to get broken down with clear fractures. The fragments had a jagged or irregular shape, with clearly visible cracks and numerous pores, and with smaller fragments or particles adhering to their surface. Notably, a large number of fragments as shown in the picture marked with the 9 in Fig. 4 appeared at the drinking water source, which was supposed to be from the same source. Film-like MPs had longitudinal tears and exhibited irregular shapes.

3.3 Soil properties, PHMs, and MPs in soils

Table 1 presented pH, organic matter, CEC, and 8 PHMs in rural soils. It was evident that S13 had the highest concentrations of Cd and Zn, followed by Pb at all sites. Meanwhile, S13 contained the highest abundance of MPs. The results for S13 were abnormal, so the data from this site was excluded for further analysis. The correlation analysis showed that there was no significant correlation between the abundance of MPs and PHMs. The EDS analysis in Figure S2 showed that a variety of elements (such as Na, Ba, Fe, Si, Al, Cl, and S) were enriched on the surface of the MPs at site S13. Notably, Zn, and Pb listed in Table 1 were detected. Zn had the highest concentration with the most prominent signal, while Pb had relatively lower contents.

4 Discussion

4.1 Abundance of MPs

The results of MP pollution in the soil on a varying spatial scale in recent years were listed in Table 2. It suggested the widespread contamination and highly heterogeneous distribution of MPs in soils around the world. The average abundance of MPs in the rural soils of Xiamen was lower than those in Yunnan province of China (Huang et al. 2021), the Mu Us Sand Land, China (Ding et al. 2021), Hangzhou bay (Zhou et al. 2020a), but higher than those in the lower reaches of Yangtze River (Cao et al. 2021) and Tibetan Plateau (Yang et al. 2022). In summary, it was concluded that rural soils in Xiamen have been polluted by MPs to some extent. Note that the soil samples in this study included a variety of soil types within the rural areas of the city and the results were representative of the level of MP pollution in the area. Of these, the MP abundance in the soil at the farmland was at a high level (4 out of the 16 sites). However, it was lower than the MP abundance in farmland in Hangzhou Bay (571 items kg^{-1}) and Yeoju City, Korea (664 items kg^{-1}), but higher than that in the suburbs of Shanghai (78 ± 13 items kg^{-1}). Unexpectedly, MP abundance in the soil was the highest at the site near the drinking water source, while it was lower in the area around the pig farm

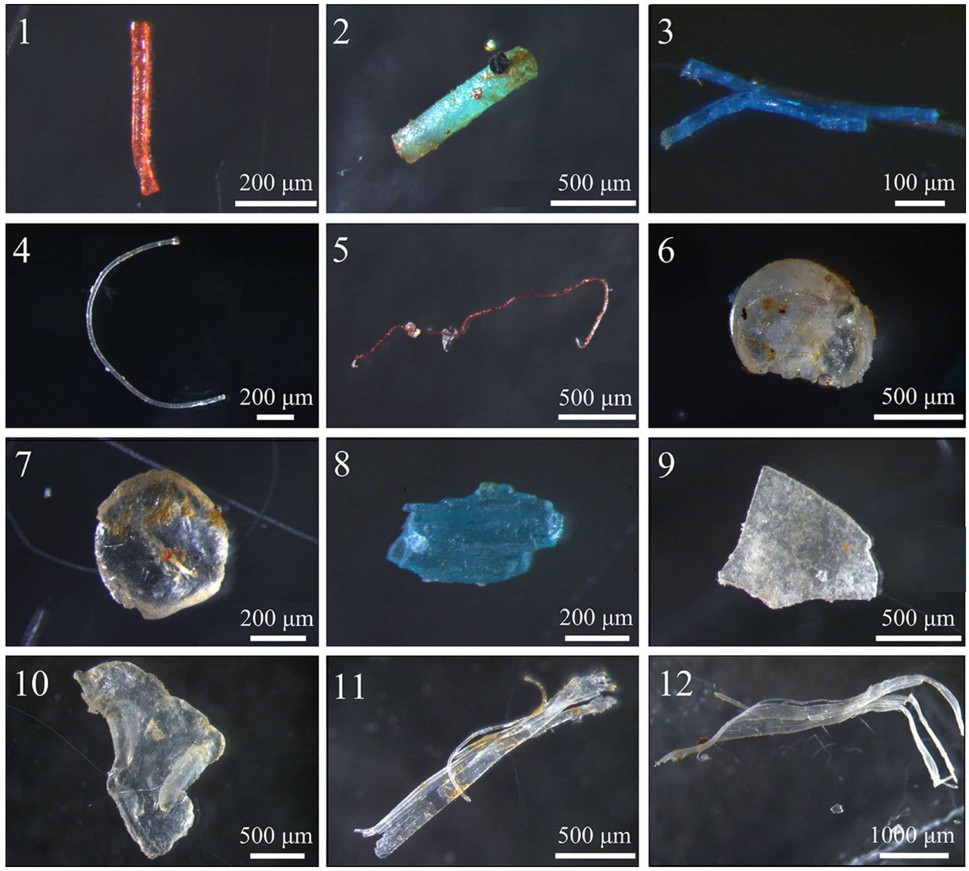

Fig. 4 Different shapes of MPs, 1–2 were line, 3–5 were fiber, 6–7 were granule, 8–10 were fragment, and 11–12 were film

and sewage treatment plant. MP pollution was also found in groundwater of a drinking-water source area in northern China (Wu et al. 2022a).

Industrial emissions and agricultural plastic wastes represented the dominant sources of soil MPs (Zhou et al. 2020a, 2018). Domestic plastic waste, agricultural plastic waste, or feeding plastic waste can be observed around the sampling sites. It indicates that human activities, agricultural and livestock waste are the main sources of MPs pollution in Xiamen. In Xiamen, reclaimed water was reused to supply agricultural irrigation and landscape recharge (Huang 2019; Li 2006). It also happened elsewhere due to the scarcity of water resources, where wastewater has been proven to be an important source of MPs in soil (Blaesing and Amelung 2018; Horton et al. 2017). Agricultural fertilizers and mulch were also possible contributors to MPs (Huang et al. 2020; Weithmann et al. 2018). Various types of industries (brick factory, textiles factory, etc.) exist in TA and HC districts. The soil MP abundance was higher in industrial areas and those close to industrial areas (Fuller and Gautam 2016; Rafique et al. 2020; Zhou et al. 2019). The industries may be the main contributor to MP pollution in the rural soils of these two districts. The highest abundance of MPs was found in XA district, indicating that it is the most contaminated by MPs from human activities, agriculture, and livestock. The high gross domestic product (GDP) of the primary industries (agriculture and animal husbandry) in XA district (Xiamen Municipal Bureau of Statistics Xiamen Investigation Team & National Bureau of Statistics 2021) also supports the assumption.

The representative sampling sites are located in XA district, and differences in MP abundance between them were probably caused by human activities, primary industries, and policy and regulatory measures. The drinking water source was close to a free-range chicken farm. The free-range chicken farm is not strictly regulated and the farm contains large amounts of domestic plastic waste and feeding plastic waste. The free-range chicken farms may be a more critical factor in such high abundance at this site. The MP pollution in groundwater of a drinking-water source area is also high related to human activity (Wu et al. 2022a). The wastes in the sewage discharge and the area around the pig farms were presumed to be comprehensively utilized and discarded. Long et al. suggested that 79.3–97.8% removal of the MP abundance at the effluent from wastewater treatment plants compared to the influent, while treated effluent from wastewater treatment plants in the Xiamen area was often discharged into Xiamen Bay (Long et al. 2019). Indeed, some effluents were also supplied to agricultural irrigation and landscape

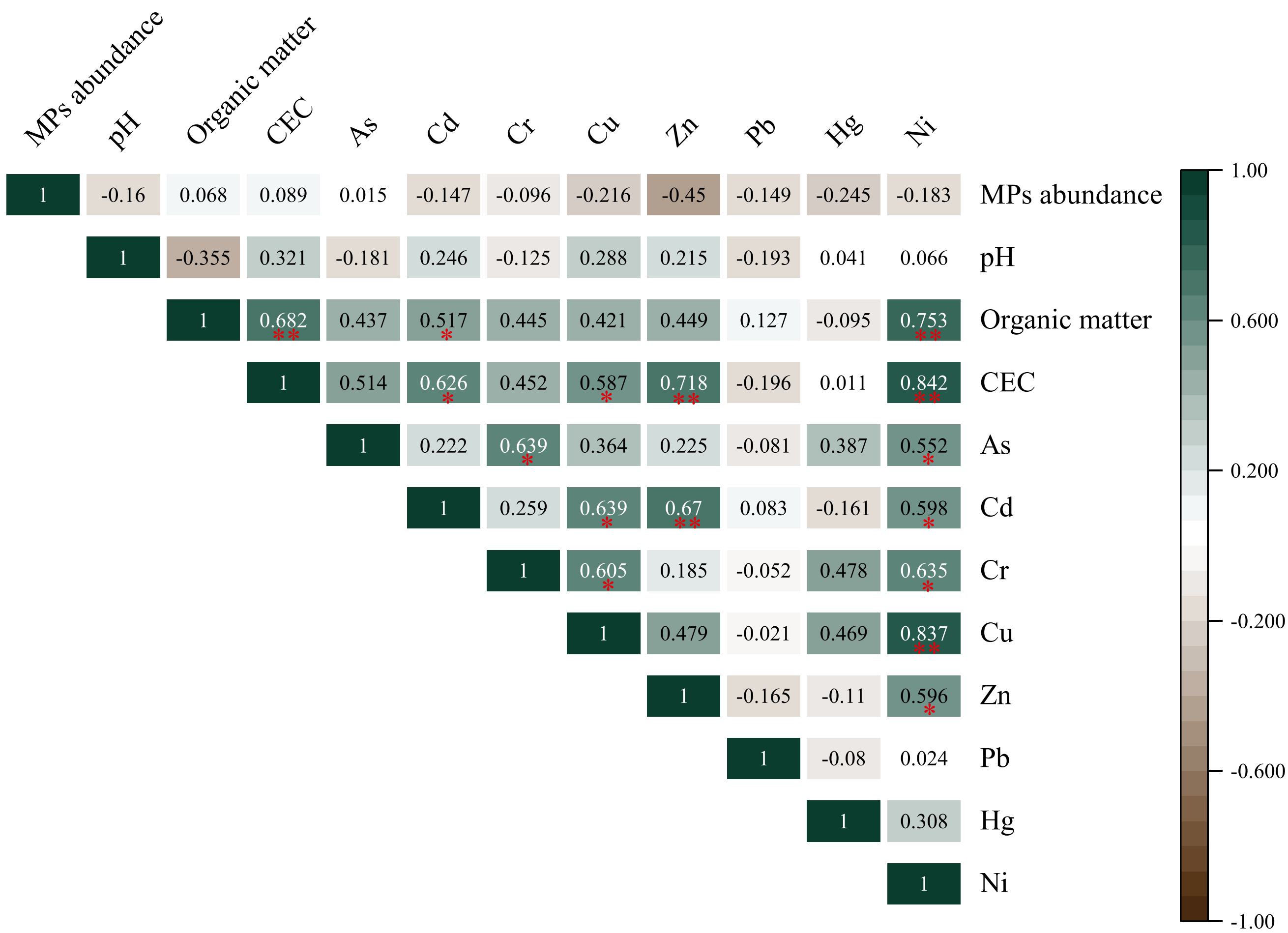

Fig. 5 Heat map of the correlation between MP abundance and the physicochemical properties (pH, organic matter, and CEC) and elemental (As, Cd, Cr, Cu, Zn, Pb, Hg, and Ni) content of the soil. (** represents a significant level of 0.01 (bilateral). * represents a significant level of 0.05 (bilateral)

recharge. In Xiamen, relevant policies and regulations require comprehensive utilization of livestock and poultry waste for stakeholders, and pig farms need to be equipped with waste storage, treatment, and utilization equipment (Fujian Provincial Department of Environmental Protection & Fujian Provincial Agriculture Department 2017).

The abundance of MPs in the forest was higher than that of Yeoju City, Korea (Choi et al. 2021) and lower than that of the suburbs of Wuhan City, central China (Zhou et al. 2019). Forests were less affected by direct anthropogenic activity than other regions, and it was suggested that the soils were more influenced by atmospheric transport (Choi et al. 2021; Scheurer and Bigalke 2018; Xu et al. 2022). Atmospheric fallout was an important source of MPs in urban soils (Blaesing and Amelung 2018). This suggested that MPs in the soils of the XA district may be attributed to atmospheric deposition from primary and secondary industries in the area.

4.2 Characteristics of MPs

Our results showed that fragments and fibers were the most common shapes in the soil of Xiamen, which was in accordance with the previous findings (Chia et al. 2021; Yang et al. 2022). Fragments were mainly derived from the degradation of plastic products (Wang et al. 2018; Zhao and Jönsson 2018; Zhou et al. 2018, 2020a). The wastewater from washing machines contained a large number of fibers. It was a challenge to eliminate the fibers in the wastewater based on current wastewater treatment techniques (Sutton et al. 2016; Zhang et al. 2021). The wastewater effluents were often reused for irrigation, which may explain the prevalence of fibrous MPs in the soil. In addition, fibers in the air were readily deposited to the soil surface by atmospheric transport (Dris et al. 2016).

PP was the dominant polymer type of most of the MPs in this study, which was in line with the results from earlier

Table 1 Soil properties and concentrations of PHMs in rural soils of Xiamen

Site	pH	Organic matter (%)	Cation exchange capacity (CEC) (cmol+/kg)	PHMs (mg kg^{-1})							
				As	Cd	Cr	Cu	Zn	Pb	Hg	Ni
S1	7.66	3.07	7.0	4.60	0.19	32	34	121	48.6	0.384	13
S2	6.93	1.95	1.0	2.960	0.18	30	22	56	37.2	0.322	8
S3	6.67	3.21	1.8	3.60	0.10	36	24	83	39.4	0.381	10
S4	6.50	2.42	3.9	4.21	0.13	46	31	91	41.0	0.772	13
S5	7.20	5.23	11.3	5.87	0.68	38	41	169	38.6	0.115	16
S6	7.44	6.77	19.3	6.13	0.32	45	35	146	34.7	0.104	20
S7	7.51	1.32	2.1	2.53	0.17	32	11	67	50.6	0.148	6
S8	7.32	1.11	n/a	2.37	0.09	27	11	51	16.8	0.074	5
S9	8.16	0.77	1.3	2.07	0.10	21	5	91	43.4	0.046	6
S10	6.44	2.29	0.8	4.81	0.15	48	20	81	34.3	0.091	8
S11	6.64	3.37	10.0	14.00	0.17	48	27	83	33.9	0.595	14
S12	6.88	3.99	12.5	5.92	0.31	36	16	165	49.3	0.123	10
S13	5.32	2.88	2.9	2.46	0.71	23	12	568	89.1	0.063	5
S14	5.00	2.32	n/a	4.14	0.06	27	9	122	31.1	0.075	8
S15	4.66	6.56	4.5	5.95	0.13	35	8	73	36.7	0.130	10
S16	5.38	4.06	1.0	4.32	0.19	34	17	44	95.6	0.088	10

n/a represents the value below the detection limit of the method

studies (Cao et al. 2021; Ding et al. 2021; Yang et al. 2022; Zhou et al. 2020a). PP is primarily used for textiles, electrical appliances, containers, furniture, packaging materials, and medical devices (Ding et al. 2021; Yang et al. 2022). Due to the low bond dissociation energy of the chemical bonds in PP, it is poorly resistant to ultraviolet (UV) (Song et al. 2017). As such, PP was more prone to break down under UV exposure than other polymers, such as PE (Gewert et al. 2015; Song et al. 2017). The polymer type of the MP fragments in the soil in this study was PP, which was probably the product of large pieces of PP plastic.

The colors of MPs in the soil were predominantly transparent and white, which was in close agreement with the results in Xiamen Bay and Jiulong River (Li et al. 2021). The result indicated that MPs in soil and water may come from the same source of pollution (Yang et al. 2022). White MPs may come from plastic bags, packaging materials, and films (Amrutha and Warrier 2020; Liu et al. 2014a). In addition, the polymer type of the MPs in the effluent of the wastewater treatment plant in Xiamen was mostly PP, while its colors were primarily transparent and white (Long et al. 2019). It was consistent with the characteristics of the MPs in the soil in this study. In particular, PP accounted for a large proportion of MP polymer types in farmland and drinking water source, which also proved that MPs may originate from the irrigation of wastewater.

The size of the MPs in this study was predominantly in the smaller particle size range (< 1 mm), similar to previous studies (Choi et al. 2021; Liu et al. 2018). Small MPs were associated with the fragmentation of larger MPs (Duis and Coors 2016). The degradation of larger MPs led to an increasing number of smaller MPs (Cao et al. 2021). MPs of small size have a more significant influence on soil properties and the growth of the plant (Yang et al. 2021). MPs may be broken down or aged through UV radiation, animal attack, and soil particle mechanical abrasion (Hidalgo-Ruz et al. 2012; Huang et al. 2021, 2020; Zhou et al. 2018).

The surface of aging MPs turned cracked, uneven, and rough. The surface area was larger due to increased voids, as well as easier accumulation of microorganisms and contaminants on the surface of MPs (Zhou et al. 2018). The beginning of the yellowing of MPs was related to the photo-oxidation process and accumulation of pollutants (Veerasingam et al. 2016). Meanwhile, the changes in the oxygen-containing groups and specific surface area of the MPs further contributed to the sorptive capacities of MPs (Frost et al. 2022; Liu et al. 2020a).

4.3 The interconnection between MPs and PHMs in soils

There was no consensus on whether the physicochemical properties of soils were affected by MPs (Qi et al. 2020; Wu et al. 2022b). The effect of MPs on the properties of the soil was related to the content, particle size, and polymer type of MPs (Feng et al. 2022; Qi et al. 2020; Yang et al. 2022; Zhao et al. 2021). Furthermore, it was claimed that soil properties (e.g., pH and dissolved organic matter content) were not the key factor in determining the abundance of MPs (Huang et al. 2021). The results showed that MPs did not show a significant correlation with pH, organic matter, and CEC of

Table 2 Comparisons of soil MP pollution elsewhere

Location	Site attribute	MP size	MP abundance (items kg^{-1})	Main polymer	Main size	Main shape	Main color	Reference
Yunnan Province, China	Cultivated land	< 5 mm	0.9–40.8; Mean: 9.8 ($\times 10^3$)	-	< 500 µm (89.3%)	Fragment (78.3%)	Transparent (49.7%)	(Huang et al. 2021)
Hangzhou Bay, Zhejiang Province, China	Agriculture land	< 5 mm	Mean: 571	PP, PE	1–3 mm	Fragment	-	(Zhou et al. 2020a)
The lower reaches of Yangtze River, China	Agricultural soils	< 5 mm	4.94–252.70; Mean: 37.32	PP	0.1–0.5 mm (49%)	Fragment (49%)	White	(Cao et al. 2021)
Tibetan Plateau, China	Soils that have not been exploited by humans	< 5 mm	5–340; Mean: 47.12	PVC, PE, PP, and PET	50–500 µm	Fibers (43.54%)	Transparent and white	(Yang et al. 2022)
Suburbs of Shanghai, China	Farmland soil (0–3 cm)	< 5 mm	Mean: 78.00 ± 12.91	PP, PE	< 1 mm	Fiber	Black	(Liu et al. 2018)
Wuhan City, central China	Woodland, vegetable plots, vacant land	10 µm– 5 mm	2.2– 69 ($\times 10^4$); Mean: 2.2×10^5	PE	10–100 µm	Fragments	-	(Zhou et al. 2019)
Yeoju City, Korea	Traffic soils Agricultural soils Residential soils Forest soils	< 5 mm	1108 664 500 160	SBR and SIS, PE, PP	< 1 mm (67%)	Fragments (66.1%),	Black (65.5%) - - -	(Choi et al. 2021)
The Mu Us Sand Land, China	Sandy land and woodland and farmland	< 5 mm	1360–4960; Mean: 2696.5	PP (53.1%), PE (24.85%), PS (15.88%)	< 0.5 mm (88%)	Fiber (39%), fragments (29%)	Black (93.47%)	(Ding et al. 2021)
Lahore, Pakistan	Urbanization (agricultural areas, public parks, house lawns, house lawns, dumping sites, drains, roadsides, wastelands/unused lands)	50 µm– 5 mm	1750–12,200; Mean: 4483 ± 2315	-	300–5000 µm	Fibers	-	(Rafique et al. 2020)
Australia	Near the industrial area	< 5 mm	300–67,500	PVC	-	-	-	(Fuller and Gautam 2016)
Xiamen, China	rural soils	0.1 mm– 5 mm	15–2222; Mean: 229 ± 523	PP (67.6%)	< 1 mm (64.4%)	Fragments (55.3%)	Transparent (59.3%)	This study

the soil. Therefore, it is speculated that MPs may have no significant effect on the physicochemical properties of the soil or that the soil properties exerted negligible impacts on the abundance of MPs. The relationship between MPs and soil physicochemical properties needs to be further explored.

The MP abundance did not correlate significantly with the concentration of PHMs in the soil, but high levels of both PHMs (Cd, Zn, and Pb) and the MP abundance were present at site S13. S13 was contaminated mainly by the waste from the chicken farm. Studies have shown that concentrations of Zn, Pb, and Cd in feed exceed national standards and that the levels of Zn, Pb, and Cd in feces are also high (Cang et al. 2004; Liu et al. 2014b, 2020b; Wang et al. 2013). Therefore, it is prone to the accumulation of metals in the soil, resulting in potential environmental risks. The EDS spectra demonstrated that Zn and Pb were detected on the surface of the MPs at site S13. MPs were recognized as carriers of pollutants. Zhou et al. (2019) measured the concentrations of heavy metals enriched in MPs and claimed that there was a strong correlation between the levels of heavy metals in soil and the heavy metals (Cd, Pb, Hg, and Mn) enriched in MPs. In addition, the content of heavy metals (*e.g.* Hg and Cd) enriched by MPs was positively correlated with the abundance of MPs (Zhou et al. 2019). MPs may be vectors for the transfer of PHMs in the soil. PHMs can adsorb to MPs, and can be easily desorbed from them under certain conditions (e.g., acidic condition) (Frost et al. 2022; Wang et al. 2019; Zhou et al. 2019).

The heavy metals might be derived from the surrounding environment or come from the inherent load (Wang et al. 2017; Zhou et al. 2019). Plastic additives, pigments, and stabilizers commonly used in plastic products contain heavy metals (Fries et al. 2013). Failure to detect all eight PHMs (As, Cd, Cr, Cu, Hg, and Ni) may be due to the non-adsorption of MPs, or their accumulation on the MP surface is too low to be detected because the accumulation of PHMs on the MP surface is influenced by the chemical properties of the PHMs and the physicochemical properties of the MP surface (Frost et al. 2022). EDS spectra showed that PHMs (Zn and Pb) were not uniformly distributed on the surface of MPs, indicating that PHMs may not be derived from those contained in the additives, pigments, and stabilizers inherent in the MPs, but were likely to be derived from the environment (Deng et al. 2020). It demonstrated that MPs were vectors of PHMs. The morphology of MPs showed that the aging of MPs in the soil would occur. The aging MPs can sequester more heavy metals, which may also pose a greater threat to the environment (Wang et al. 2019). The coexistence of MPs and heavy metals may change metal mobility, soil fertility, and soil microbial diversity and functions, which poses the greater negative effects on terrestrial organisms such as earthworm *Eisenia foetida* (Feng et al. 2022; Zhou et al. 2020b).

5 Conclusion

In this study, soil samples were collected and analyzed for MPs and PHMs contamination in Xiamen, and their interconnections was evaluated. The mean abundance of soil MPs was 229 ± 523 items kg^{-1}, while it spanned from 15 to 2222 items kg^{-1}. The abundance of MPs in XA district (333 ± 640 items kg^{-1}) was significantly higher than that in HC district (83 ± 15 items kg^{-1}), TA district (59 ± 15 items kg^{-1}), and JM district (27 ± 4 items kg^{-1}). The results of the analysis of MPs samples using EDS at the most contaminated sampling site (drinking water source) indicate that the PHMs (Zn and Pb) on their surfaces are derived from the environment. There was no significant correlation between MP abundance and physicochemical properties (pH, soil organic matter, and CEC) and PHMs in the soil. In summary, it demonstrated that MPs may be vectors for the transfer of PHMs or MPs and PHMs in soil all affected by human activities. The sources of soil MPs in Xiamen are mainly industrial, agricultural, and human activities, including manufacturing, construction, animal husbandry, sewage irrigation, atmospheric deposition. Representative sampling sites with severe MP pollution may be affected by multiple sources. This study provides insights into combined contamination of MPs and PHMs in rural soils in Xiamen, which will help formulate effective pollution abatement measures.

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Data availability All study data are included in the article and supplementary material.

Declarations

Conflict of interest The authors declare no competing interests.

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