Journal of Soils and Sediments (2023) 23:936–946
https://doi.org/10.1007/s11368-022-03341-6

SOILS, SEC 5 • SOIL AND LANDSCAPE ECOLOGY • RESEARCH ARTICLE

Occurrence, distribution, and characteristics of microplastics in agricultural soil around a solid waste treatment center in southeast China

Xi Liu[1] · Huirong Lin[1] · Sheng Xu[1] · Yu Yan[1] · Ruilian Yu[1] · Gongren Hu[1]

Received: 5 May 2022 / Accepted: 16 September 2022 / Published online: 28 September 2022

Abstract

Purpose In recent years, microplastic (MP) contamination has raised enormous concern. However, data on the influence of solid waste treatment systems on MP pollution around agricultural soil are lacking. This study investigated the distribution and characteristics of MPs in agricultural soil surrounding a solid waste treatment center in southeastern China.

Materials and methods Fifty-seven agricultural topsoil samples around the solid waste treatment center were collected. The samples were pretreated by drying, flotation separation using NaCl solution, and digestion by H_2O_2. The abundance and morphological characteristics of MPs were determined by a microscope, followed by Raman spectroscopy analysis identified polymer types and SEM–EDS analysis observed surface morphology and the type of metals accumulated on the MPs.

Results and discussion Soil MPs' abundance ranged from 280 to 2360 items/kg, while a higher abundance of MPs was distributed in the downwind area. The < 1-mm MPs were dominant, and white fragment MPs were widely found. Polyethylene (52.86%) and polypropylene (27.14%) were the most common. Moreover, SEM–EDS images illustrated that MPs were significantly weathered and showed the uneven distribution of metal(loid) elements on the surface, implying that MPs may migrate as heavy metal vectors to threaten agroecosystem safety.

Conclusions This study reveals the distribution and characteristics of MPs in agricultural soil surrounding a solid waste treatment center in southeastern China, as well as the potential source of soil MPs, and provides systematic data for further research on MP pollution in agricultural soil.

Keywords Microplastics · Agricultural soil · Distribution · Solid waste treatment center

1 Introduction

Plastics are widely used due to their superior mechanical properties, while the ensuing plastic pollution has created enormous challenges to ecosystems. In particular, the demand for single-use plastic products has skyrocketed with the outbreak of the COVID-19 pandemic (Hu et al. 2022). Global plastic waste production is estimated to be 1.6 million tons per day, and approximately 3.4 billion single-use facemasks/face shields are discarded every day (Benson et al. 2021). Microplastics (MPs; < 5 mm in size) have ubiquitously found in the atmospheric environment (Liao et al. 2021; Wang et al. 2020b), aquatic environment (Elgarahy et al. 2021; Koelmans et al. 2019), and terrestrial environment (de Souza Machado et al. 2018; Wang et al. 2019), even in organisms (Lu et al. 2019; Zhang et al. 2020), which has been regarded emerging environmental contaminant. So far, studies on MPs have mainly focused on aquatic environments, while their occurrence in terrestrial ecosystems has been studied to a much lesser extent.

Agricultural soils are considered as a crucial sink of MPs through the inputs from mulching films, sewage irrigation, atmospheric deposition, and compost, negatively affecting agroecosystems and plant productivity (Ng et al. 2018). A growing body of evidence has shown that MPs in soil have detrimental impacts on soil biota, as well as alter the soil properties and biogeochemical cycles (de Souza Machado et al. 2019; Guo et al. 2020; Khalid et al. 2020; Wang et al. 2021). For example, Jiang et al. (2019)

Responsible editor: Claudio Bini

✉ Huirong Lin
hrlin@hqu.edu.cn

1 Department of Environmental Science and Engineering, Huaqiao University, Xiamen 361021, China

found that MPs cause oxidative damage and genotoxicity in *Vicia faba*, meanwhile, Yu et al. (2020b) discovered that MPs induce oxidative stress and intestinal injury in nematodes. Moreover, MPs are easily transferred into groundwater systems, creating a hazard by chemical additives releases (Ren et al. 2021). Apart from their small size, complex nature, and potential toxicity, MPs can act as vectors of dangerous pollutants and pathogens, posing indeterminate ecotoxicological risks through bioaccumulation and biomagnification in the food chain (Bradney et al. 2019; Yu et al. 2020a). The increasing MP pollution in soil may threaten terrestrial food systems and human health. It has been estimated that humans might ingest 80 g of MPs through edible plants daily (Ebere et al. 2019), and MPs have been detected in human food (Jin et al. 2021), human placenta (Ragusa et al. 2021), and human blood (Leslie et al. 2022), showing the potential risk to human health. Additionally, as hotspots of antibiotic resistance genes and potential pathogens, soil "plastisphere" exacerbates the antibiotic resistance issues in soil (Liu et al. 2021; Zhu et al. 2021). Therefore, research on MP pollution in agricultural soil is of great significance.

Co-occurring MPs and heavy metals in soil pose an alarming threat to soil biodiversity and agroecosystem (Roy et al. 2022). Heavy metals, the nonbiodegradable inorganic pollutants, have long-term negative impacts on human and ecosystem health. Corresponding studies have highlighted that the simultaneous exposure to MPs and heavy metals in soils joint affects soil properties, microbial diversity and functions (Feng et al. 2022), root symbiosis, and plant performance (Wang et al. 2020a), and their combined toxicity is tremendously dangerous than individual toxicity (Khalid et al. 2021; Yan et al. 2020). Moreover, the weathering of MPs can significantly promote their heavy metal adsorption capacity (Chen et al. 2022). A significant amount of plastic waste eventually ends up in landfills or incineration plants. As the MP reservoirs, mismanaged landfills can transfer MPs to their surroundings via an air-borne pathway or the leakage of leachate (He et al. 2019; Rillig 2012). More MPs were detected in the atmospheric fallout collected from landfills (Thinh et al. 2020) and in the groundwater samples around a landfill (Natesan et al. 2021). Additionally, heavy metal pollution was more prone to occur in the soil around waste incineration plants and the operation of waste incineration plants may facilitate the accumulation of heavy metals in soil (Ma et al. 2018). It is more likely that the combined pollution of MP and other pollutants occurs in the soil surrounding the solid waste treatment center. However, to date, the occurrence of MPs in agricultural soils around solid waste treatment centers has not been explored. This study systematically investigated the occurrence, spatial distribution, and characteristics of MPs in agricultural soil near a solid waste treatment center in southeastern China to provide valuable information for estimating and monitoring MPs' presence in the complex agroecosystem.

2 Materials and methods

2.1 Studied area and sampling methods

A solid waste treatment center which is located in Xiamen, southeast China (N 24°32′–24°50′, E 118°10′–118°27′) was chosen as a studied area. It is the only multi-functional large-scale solid waste comprehensive treatment base in this city that integrates domestic waste classification and treatment, fermentation and fertilizer production, sanitary landfill, incineration and power generation, animal harmlessness, waste recycling, and water reuse, and it is responsible for the disposal of domestic garbage, medical garbage, and industrial hazardous waste (Fig. S1). Equipped with treatment plants such as landfills and waste incineration plants, the solid waste treatment center was first operated in 2008 and now handles more than 3700 tons of domestic waste and more than 200 tons of kitchen waste per day. The studied area has a typical subtropical oceanic climate and the rainfall increases due to the influence of typhoons from July to September each year, with an average annual rainfall of 1143.5 mm and relative humidity of 77%.

Since easterly wind prevails throughout the year and the eastern part is a mountainous area, the studied area was classified into upwind, center, and downwind areas. Taking the solid waste incineration plant as the center, the 500 × 500 m grid method was used to collect 57 agricultural soil samples with a depth of 0–20 cm at a total area of 36 km^2 along with a 3.0-km extension from north to south and east to west (Fig. 1). There were 31 sampling points in the upwind area (S1–S31), 8 sampling points in the center area (S32–S39), and 18 sampling points in the downwind area (S40–S57). Five sub-samples were collected from each sample point using the five-point sampling method and a pre-cleaned stainless shovel in October 2020. After removing litter, grassroots, insect shells, gravel, and other impurities, the five sub-samples were mixed and homogenized into a composite sample on site. Finally, about 500 g of the composite sample was packed in a clean glass bottle, then transported to the laboratory. In the laboratory, the soil samples were wrapped in aluminum foil and dried to constant weight in a drying oven at 30 °C.

2.2 Extraction of MPs

MPs in the soil samples were separated and extracted using the density separation method used by Thompson et al. (2004) but with slight adjustments. For each sample, 50 g of dried soil was placed in a glass beaker and mixed with

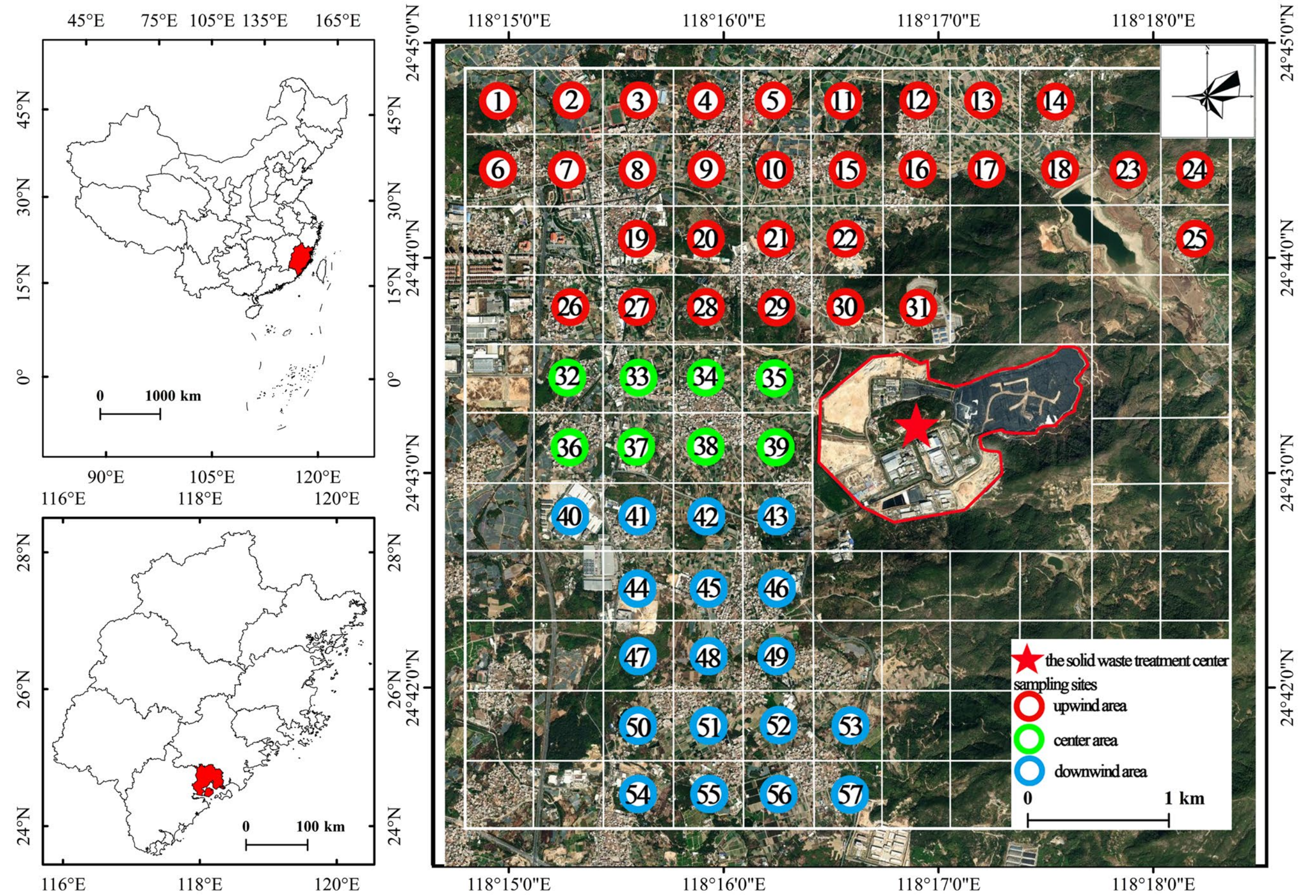

Fig. 1 Geographic location of the studied area. Since there are mountains in the eastern study area, the sampling area is selected on the left side of the study area

saturated NaCl solution (1.2 g/cm^3, dissolved in Milli-Q water), and the mixture was stirred for 10 min to mix thoroughly and left for 24 h. After removing the supernatant, the saturated NaCl solution was added to the beaker with soil again, and this step was repeated three times to fully extract MPs. The collected supernatant was passed through a 2-mm sieve and then filtered with a vacuum filtration device with a glass-fiber filter membrane (Sartorius, diameter 50 mm, pore size 0.45 μm). The material on the filter membrane was rinsed slowly with saturated NaCl solution to a clean glass Erlenmeyer flask and floated again to avoid clogging of filter membrane for soil particles are not completely separated from the NaCl solution. Following density separation, H_2O_2 (30%, v/v, XIHUA) was added to the conical flask containing the supernatant at a ratio of 10:1, then transferred to a 70 °C water bath and heated until the organic matter was completely digested. The digested solutions were cooled down and filtered through a 0.45-μm glass-fiber filter membrane. The MP-containing filter membrane was moved to a clean glass petri dish, dried, sealed, and preserved for further analysis.

2.3 MPs' identification

The color, shape, and size of the suspicious MPs on the membrane were visually identified under a microscope (Olympus SZ61, Japan), and the quantity was recorded (Fig. 2). There were three shapes observed: fragments (flaky with obvious outline), fibers (slender strip), and particles (stereo particles), and six colors: white (transparent included), blue, red (pink included), black, yellow, and green. The chemical components of the representative MPs and suspect particles in the different membranes were determined using a Raman microscope (Renishaw in Via, UK, spectral range: 100–3200 cm^{-1}, incident laser: 785 nm). Raman micro-spectroscopy analysis was repeated three times in three different runs under the same conditions to guarantee the accuracy of the results (Fig. S2) (Sobhani et al. 2019; Dong et al. 2020).

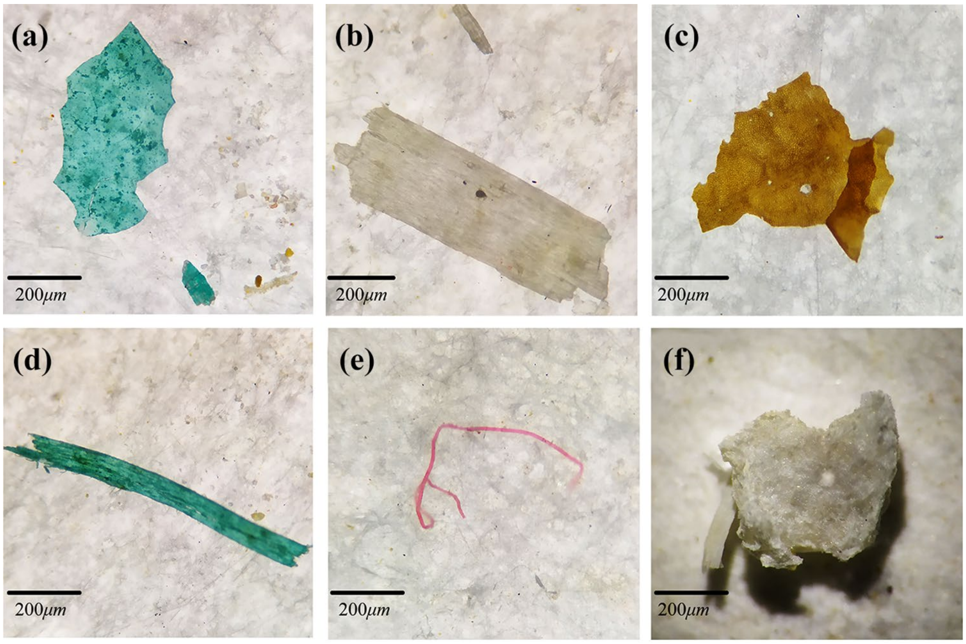

Fig. 2 Typical image of MPs under the microscope: fragment (**a**–**c**), fiber (**d**, **e**), and particle (**f**)

2.4 SEM–EDS analysis

After being identified by Raman analysis, the MP was coated with a thin film of platinum and placed under a scanning electron microscope (SEM, Hitachi S4800, Japan) to observe the surface morphology, and an energy spectrometer (X-Act, Oxford) was used to obtain the metal elements attached to the MPs' surface. The visualization was repeated three times in different positions to ensure accuracy (Wang et al. 2017).

2.5 Physico-chemical parameters of soils

The dried soil samples were ground through a 0.15-mm sieve. Soil pH and electrical conductivity (EC) were measured using suspended samples with soil/water ratios of 1:2.5 and 1:5, respectively. Total organic carbon (TOC) in the soil is determined by microwave digestion. The data of physico-chemical parameters of soils are listed in Table S1.

2.6 Quality control

To prevent plastic contamination during the experiment, only glass utensils were used and rinsed with Milli-Q water and continuously covered with aluminum foil. Throughout the trial, the researchers donned white cotton lab coats and nitrile gloves. Ten blank control experiments were conducted to determine the MP pollution induced by Milli-Q water, reagents, and experimental processes, but no MPs were detected, showing that the impact of the experimental environment can be ignored.

2.7 Statistical analysis

The statistical analysis was performed by IBM SPSS 22.0, and one-way ANOVA was used to compare the significant differences in the abundance of MPs in different studied areas. All figures and tables were drawn using ArcGIS 10.8, Excel 2019, and Origin 2021.

3 Results and discussion

3.1 Abundance and distribution of MPs

MPs were widely observed in the 57 soil samples, and there were significant differences in their spatial distribution. The overall abundance of MPs varied from 280 to 2360 items/kg, with an average of 820 items/kg. The MP concentration in the upwind, center, and downwind region ranged from 400 to 1480 items/kg, 280 to 1240 items/kg, and 340 to 2360 items/kg, respectively (Fig. 3a). The highest value occurred at site S48, located in the village area in the downwind area. Abundant MPs were not found in the samples near the solid waste center but found in those closer to the villages or roads in the downwind area. Unexpectedly, no statistical differences were found in the abundance in the downwind, center, and upwind areas, while the mean abundance of MPs in the downwind area was higher than that in other areas (Fig. 3b). These different distribution observations might be explained by the irregular planting patterns in the sampling area. Since the study area is not a large-scale vegetable planting area, and there are irregular planting patterns, the villagers tend

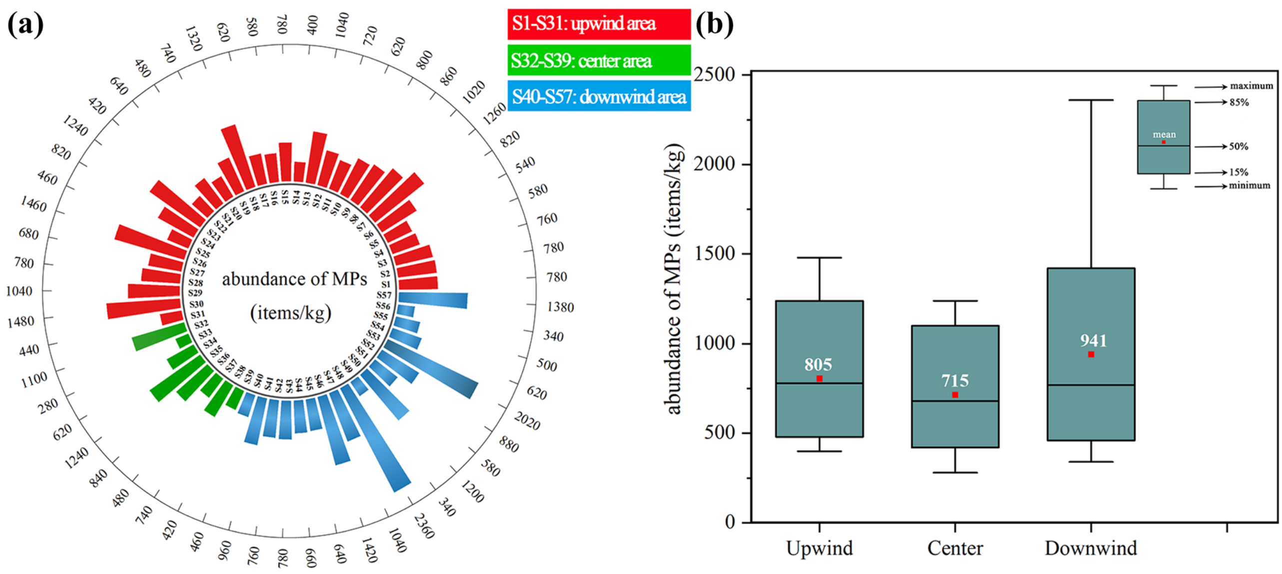

Fig. 3 Abundance of MPs at each sampling point (**a**), and boxplots for abundance analysis of MPs, no significant differences were detected (**b**)

to apply mulch film technology to some areas with fragile vegetables to increase their production. A higher abundance of MPs in the downwind area implied that the solid waste treatment center might have a small contribution to MP pollution in the surrounding agricultural soils. Loppi et al. (2021) found that the impact of MPs on air emissions from landfills was spatially limited by detecting the deposition of MPs on lichens in the vicinity of landfills. The solid waste treatment center's limited effect in this study might be attributed to its strong management. For example, modern processing techniques are employed, the operating area and time are substantially reduced, and the fog cannon cars continuously spray special medicine for disinfection and deodorization during the working period. All these measures may have contributed to lessening the pollution of the solid waste center to the surrounding soil.

Compared with the gathering research on MPs in agricultural soil (Table 1), the MPs' pollution level in this study is moderate. The abundance of MPs in different research regions varies due to diverse factors such as pollution sources, soil properties, planting patterns, extraction, and quantification methods. The concentration of MPs in farmland soil around an e-waste dismantling zone in China reached up to 22,800 items/kg, with e-waste as the primary source (Chai et al. 2020). The cultivated soil of the Yunnan Plateau, where the planting industry was the basis, contained 900–40,800 items/kg of MPs (Huang et al. 2021). Higher MP concentrations were found in the mulching farmlands than in non-mulching farmlands (Zhou et al. 2020a). Owing to the limitation of the density of the flotation solution, high-density MPs failed to float, which may have resulted in an underestimated MPs abundance in this study. Moreover, the studied area is far away from the industrial area, so industrial sources could not be considered, implying agricultural activities might be the primary cause of MP contamination.

3.2 Size, color, shape, and composition characteristics of MPs

The most frequent plastic particle size was less than 0.05 mm, accounting for 65.8% of the total samples, followed by the particle size of 0.05–1 mm (20.2%) and 1–2 mm (14.0%) (Fig. 4a). Similar to previous research (Wang et al. 2022), the particle size distribution showed a tendency that the smaller the particle size, the larger the proportion, attributing to the formation of more small particles by aging (ultraviolet radiation, mechanical plowing, and biodegradation). The < 1 mm MPs were detected in greater abundance in the downwind area than in the center and upwind areas, which can be ascribed to the fact that smaller and lighter MPs may be carried by the wind (Rezaei et al. 2019), and to some extent, it was revealed that the solid waste center may contribute to the MPs in downwind area via atmospheric deposition. Studies have demonstrated that the smaller the particle size of MP, the greater pollutant adsorption capacity and the easier it is for it to be swallowed by soil creatures or migrate to deeper layers of soil, causing harm to soil animals and the agricultural ecosystem (Boots et al. 2019; Lahive et al. 2019). Given the higher risk of small-particle MPs, more research is urgently required on their distribution and toxicity.

Table 1 Characteristics of MPs in agricultural soil in different regions

Soil type	Location	Abundance (items/kg)	Size range (mm)	Shape	Type	References
Agricultural soils	Southeast Germany	0.34–0.36	1–5	Fragment, film, fiber	PE, PP, PS	(Piehl et al. 2018)
Vegetable lands	Mauritius	320–420	0.25–4.9	Fibers, flake, foam, film, fragment	PP, PE, PA, PS, EVA	(Ragoobur et al. 2021)
Vegetable fields	Wuhan, China	320–12,560	0.02–5	Fiber, fragment, microbead, foam	PA, PP, PS, PVC, PE	(Chen et al. 2020)
Agricultural soils	Shouguang, China	310–5698	0–5	Fragments, film, fiber, pellet, foam	PP&EPC, PE, PS, PES	(Yu et al. 2021)
Agricultural soils	Shaanxi, China	1430–3410	0–5	Fiber, film, fragments, pellets	PS, PE, PVC, PET	(Ding et al. 2020)
Farmland soils	Tibetan Plateau, China	20–110	0–5	Fibers, film, fragment, sphere, foam	PE, PP, PS, PET	(Feng et al. 2020)
E-waste polluted soils	Guiyu, China	12,300 ± 10,500	0–5	Granule, fragment, film, fiber, pellet column	PS, PP, PE, PVAL	(Chai et al. 2020)
Cultivated soils	Yunnan, China	900–40,800	0–5	Fiber fragment	/	(Huang et al. 2021)
Farmlands soils	Hangzhou Bay, China	Mulching: 571.2 Non–mulching: 262.7	0.05–5	fragment, fibers films	PE, PP, PA, PE and PP	(Zhou et al. 2020a)
Agricultural soils	Xiamen, China	280–2360	0–2	Fragment, fiber, particle	PE, PP, PS, PET	This study

The color distribution of MPs was significantly different: white (58.20%), blue (12.66%), black (9.47%), red (8.50%), yellow (7.52%), and green (3.65%) (Fig. 4b), which is related with the characteristics of local plastic pollution. White plastic products such as plastic film are widely used in cultivated land. Moreover, the colored MPs will weather and turn white, releasing harmful additives and intermediates (oligomers and dissolved organic matter (DOM)) to cause ecological risk (Zha et al. 2021). In this study, fragments accounted for 58.4% of all samples were the dominant type of MPs, followed by fibers (31.86%) and particles (9.74%) (Fig. 4c). Weithmann et al. (2018) discovered that all compost samples with different substrates were rich in MPs, of which fragments and particles accounted for a large proportion. A higher proportion of fibers was detected in the downwind area, which is frequently found in irrigation water and atmospheric deposition. Additionally, different shapes of MPs have distinct mobility, the particles are more likely to migrate to deep soil, whereas the fragments and the fibers may hinder the migration of MPs in the soil (Zhou et al. 2020b).

The components of MPs were identified as polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyethylene terephthalate (PET). The most common polymer types identified were PE (52.86%) and PP (27.14%), while PS (11.43%) and PET (7.14%) were the second most abundant in all samplings (Fig. 4d). PE and PP are widely utilized in manufacturing and daily life as raw materials for a variety of packaging, containers, plastic mulch, pipes, and other plastic products. In this study, the high abundance of PE and PP was attributed to the extensive use of plastic film and compost. Huang et al. (2020) confirmed that plastic mulching was the main source of MPs in agricultural soils through the research on plastic residues on agricultural land in China in the past 5 years. MPs were widely detected in rural domestic waste compost (Gui et al. 2021) and livestock manure (Huerta Lwanga et al. 2017; Yang et al. 2021). Moreover, PS is widely used in the manufacture of transparent films, daily decoration, and packaging, particularly in cosmetics products. Likewise, field surveys of this study discovered that numerous plastic mulch waste was removed improperly, plastic garbage such as plastic bags or bottles used to contain fertilizers and pesticides were scattered everywhere, and composting was applied. In addition, wastewater irrigation was observed in the analyzed zone. PET is mainly applied in the textile industry, and PET-MPs are transferred to the environment through domestic sewage. In recent years, certain evidence indicates that abundant MPs have been detected in terrestrial water bodies such as rivers, lakes, and ponds and can be disseminated in agricultural soils as a result of irrigation. For example, PET-MPs (30.2%) were widely identified in agricultural land irrigated with wastewater in Baoding, China, (Du et al. 2020). Based on these results, it can be concluded that agricultural activities contributed significantly to

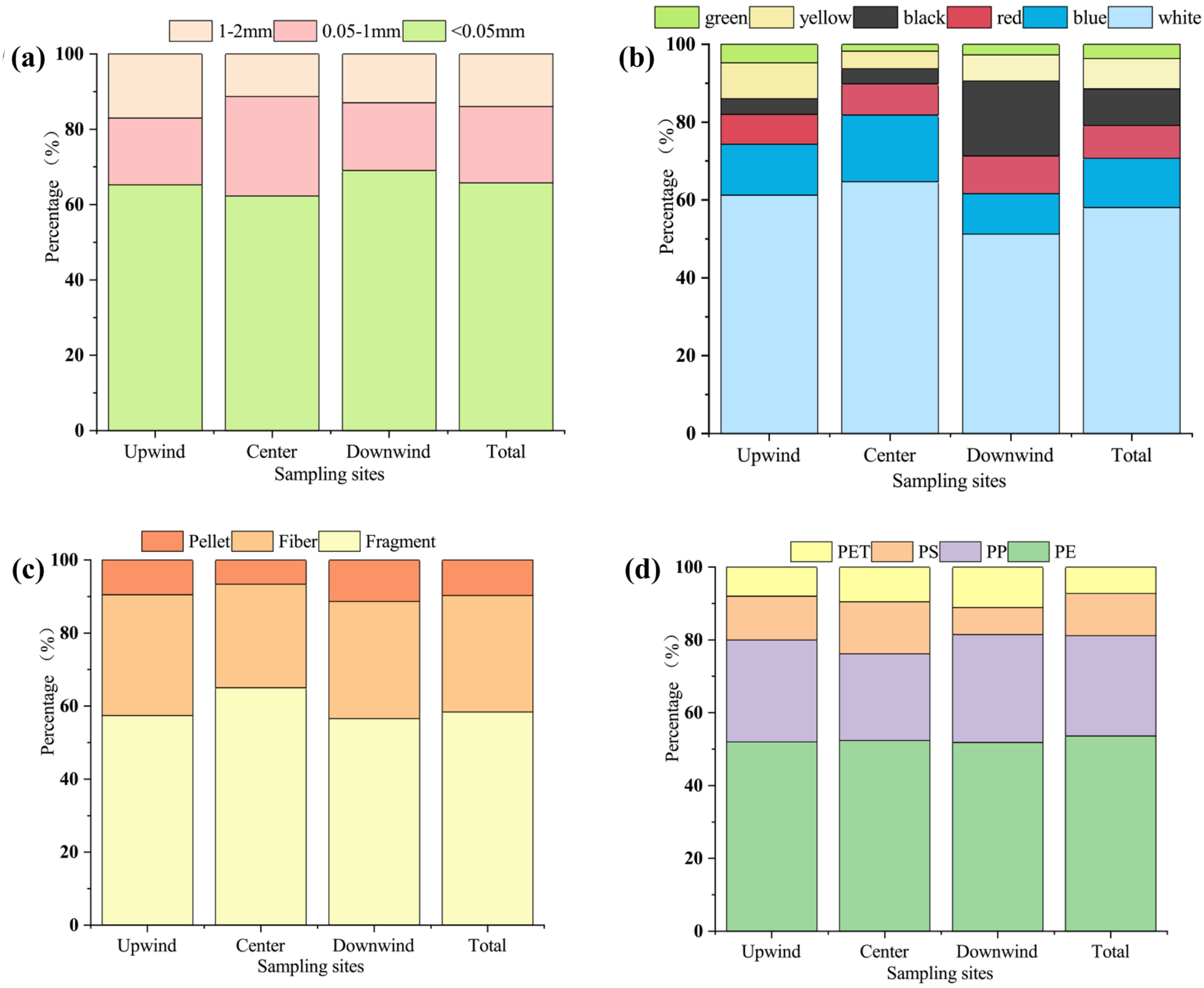

Fig. 4 Physicochemical characteristics of MPs in different study areas. **a** Size characteristics. **b** Color characteristics. **c** Shape characteristics. **d** Component composition

MP pollution in this study. Additionally, MPs can enter soils by road dust, surface runoff, and atmospheric deposition which may explain why MPs are greater in downwind locations. Therefore, further research works on the contributions of atmospheric MPs need to be carried out subsequently.

3.3 Surface morphology of MPs

Different types of MPs randomly selected presented complex surface morphologies via SEM. The MPs have weathered as a result of long-term exposure to the soil environment and show aging features like rough and porous surfaces. On the surface of the fragments, there are numerous fissures and uneven rips (Fig. 5a). The fibers are badly worn, with no original shape and many linear convex plastic residues generated by ripping; filiform fibers, in particular, have been eroding more severely (Fig. 5b,c). The particles are heavily irregularly damaged, with some undigested strips clinging to the surface, showing a complicated structure (Fig. 5d). Long-term UV light, frequent physical abrasion, and microbes all played an important role in the weathering of MPs in the soil environment, altering their surface shape and characteristics (Duan et al. 2021).

3.4 Elements attached to the surface of MPs

SEM–EDS analysis of the surface element distribution of the MP samples was carried out for 9 metal(loid)s (Cd, Hg, Cr, Fe, Mn, As, Zn, Cu, Ni) (Fig. 6). The EDS image demonstrated that more diverse metal(loid) elements can be detected on the surface of MPs with aging characteristics such as substance attachments, depressions, protrusions,

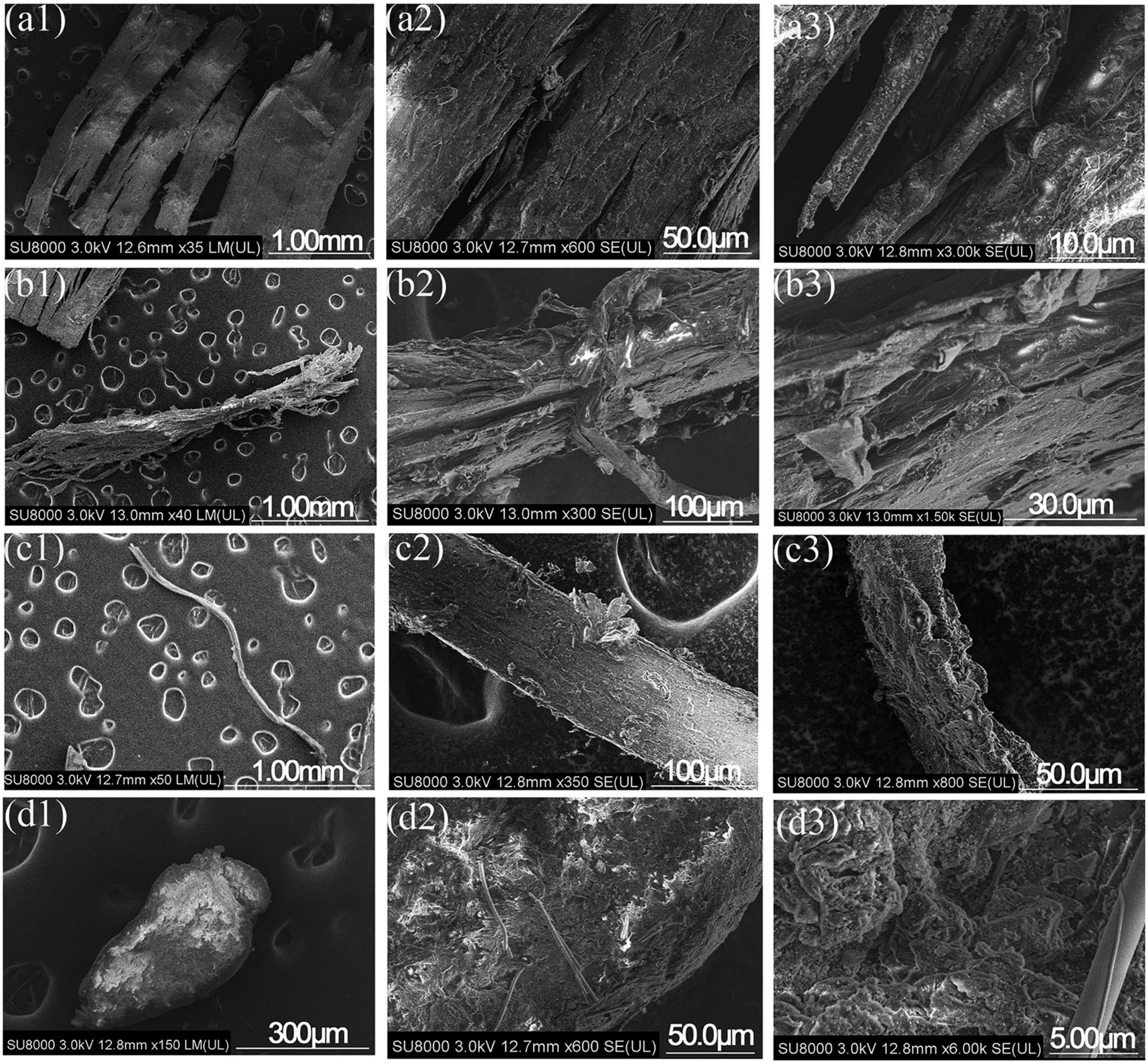

Fig. 5 SEM images of different shapes of MPs at different magnifications. **a** Fragments. **b** Fibers. **c** Filamentous fibers. **d** Particles

and cracks or broken edges. The increased specific surface area, oxygen-containing functional groups, and surface electronegativity of the aged MP result in greater sorption to metals (Duan et al. 2021). The presence of metal elements on MPs can be linked to inherent load and external environment adsorption. Metals were added to plastic throughout the production process as stabilizers, pigments, or catalysts to improve its performance and esthetics. Laboratory simulation experiments and environmental monitoring data have indicated that MPs can adsorb metals from the external environment (Godoy et al. 2019; Sighicelli et al. 2018). In this study, there are different metal elements observed on different surface sites of individual MP, suggesting that part of the metals attached to the surface of the MPs originated from the external environment. In other words, the MPs can act as carriers of metals to facilitate the accumulation of heavy metals in soil and aggravate soil complex pollution. Zhou et al. (2019) confirmed that the MPs in soil were vital transport carriers of metals, and heavy metal content in MPs was significantly impacted by soil content levels. Given the mobility and capacity of MPs to absorb and accumulate metals, soil MP contamination deserves more attention and research.

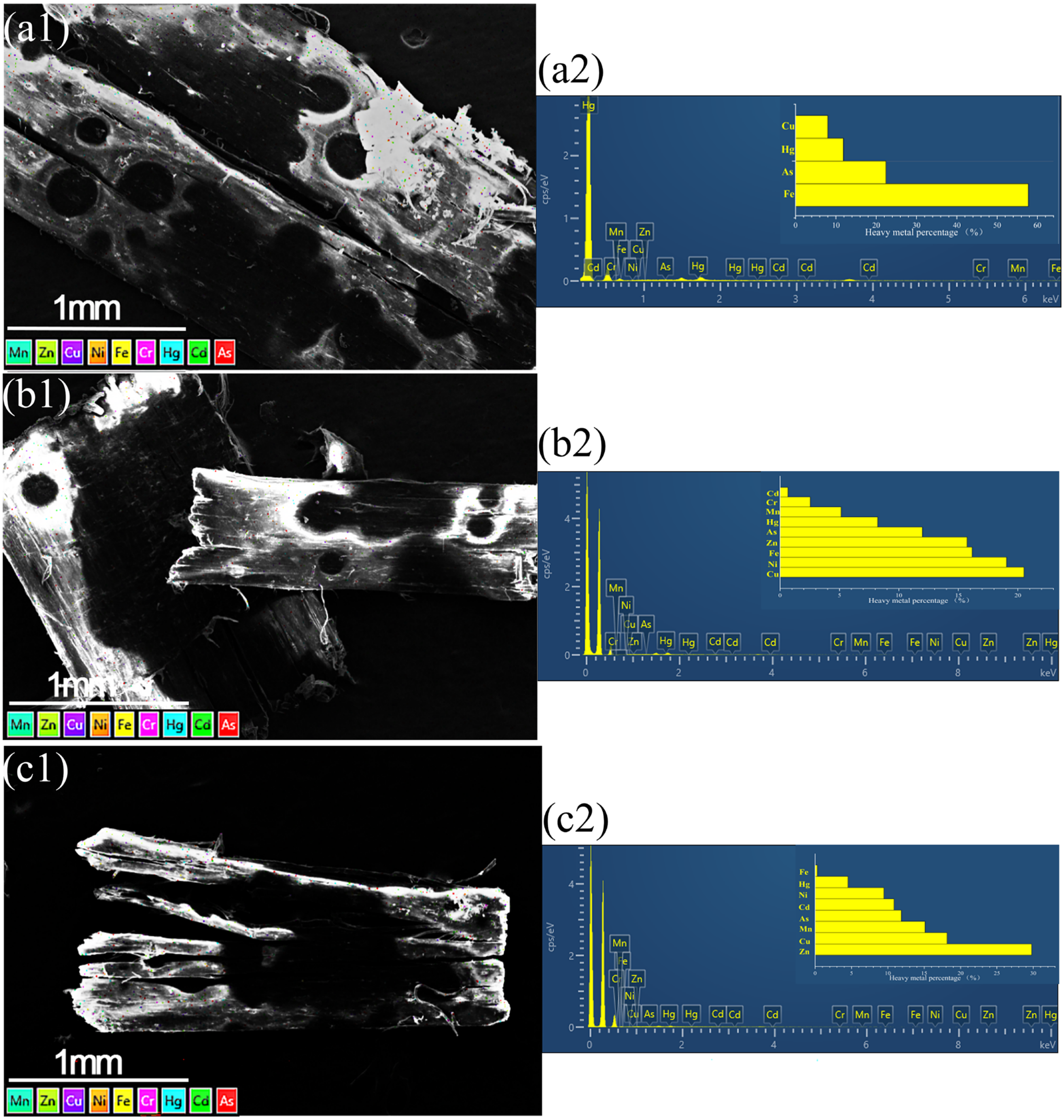

Fig. 6 SEM–EDS images of MPs in different study areas: **a** upwind area, **b** center area, and **c** downwind area

4 Conclusion

This study described the occurrence, distribution, and characteristics of MPs in agricultural soil around a solid waste treatment center in southeast China. The < 1-mm MPs were prevailing, while PE and PP fragments were commonly detected. MPs generally exhibited complicated weathered surfaces that had the potential to absorb heavy metals. The presence and distribution of MPs in soil samples have been considerably influenced by agricultural operations. The solid waste treatment center has a small contribution to the propagation of MPs showing that well-management could prevent the spread of MPs. Nevertheless, higher MP levels found in the downwind area, especially small-sized ones, revealed certain potential risks. Further research works are urgently required to reveal the distribution of the atmospheric MPs in areas along different wind directions.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11368-022-03341-6.

Acknowledgements The work was supported by the Research Fund Program of Guangdong Provincial Key Laboratory of Environmental Pollution Control and Remediation Technology (2020B1212060022). We thank the staff at the Instrumental Analysis Center of Huaqiao University for their help.

Declarations

Conflict of interest The authors declare no competing interests.

References

Benson NU, Bassey DE, Palanisami TJH (2021) COVID pollution: impact of COVID-19 pandemic on global plastic waste footprint. Heliyon 7(2):e06343

Boots B, Russell CW, Green DS (2019) Effects of microplastics in soil ecosystems: above and below ground. Environ Sci Technol 53(19):11496–11506

Bradney L, Wijesekara H, Palansooriya KN, Obadamudalige N, Bolan NS, Ok YS, Rinklebe J, Kim KH, Kirkham MB (2019) Particulate plastics as a vector for toxic trace-element uptake by aquatic and terrestrial organisms and human health risk. Environ Int 131:104937

Chai B, Wei Q, She Y, Lu G, Dang Z, Yin H (2020) Soil microplastic pollution in an e-waste dismantling zone of China. Waste Manage 118:291–301

Chen M, Liu S, Bi M, Yang X, Deng R, Chen Y (2022) Aging behavior of microplastics affected DOM in riparian sediments: from the characteristics to bioavailability. J Hazard Mater 431:128522

Chen Y, Leng Y, Liu X, Wang J (2020) Microplastic pollution in vegetable farmlands of suburb Wuhan, central China. Environ Pollut 257:113449

de Souza Machado AA, Kloas W, Zarfl C, Hempel S, Rillig MC (2018) Microplastics as an emerging threat to terrestrial ecosystems. Global Change Biol 24:1405–1416

de Souza Machado AA, Lau CW, Kloas W, Bergmann J, Bachelier JB, Faltin E, Becker R, Görlich AS, Rillig MC (2019) Microplastics can change soil properties and affect plant performance. Environ Sci Technol 53:6044–6052

Ding L, Zhang S, Wang X, Yang X, Zhang C, Qi Y, Guo X (2020) The occurrence and distribution characteristics of microplastics in the agricultural soils of Shaanxi Province, in north-western China. Sci Total Environ 720:137525

Dong M, Zhang Q, Xing X, Chen W, She Z, Luo Z (2020) Raman spectra and surface changes of microplastics weathered under natural environments. Sci Total Environ 739:139990

Du C, Liang H, Li Z, Gong J (2020) Pollution characteristics of microplastics in soils in southeastern suburbs of Baoding City, China. Int J Env Res Pub He 17(3):845

Duan J, Bolan N, Li Y, Ding S, Atugoda T, Vithanage M, Sarkar B, Tsang KMB (2021) Weathering of microplastics and interaction with other coexisting constituents in terrestrial and aquatic environments. Water Res 196:117011

Ebere EC, Wirnkor VA, Ngozi VE (2019) Uptake of microplastics by plant: a reason to worry or to be happy? World Scientific News 131:256–267

Elgarahy AM, Akhdhar A, Elwakeel KZ (2021) Microplastics prevalence, interactions, and remediation in the aquatic environment: a critical review. J Environ Chem Eng 9(5):106224

Feng S, Lu H, Tian P, Xue Y, Lu J, Tang M, Feng W (2020) Analysis of microplastics in a remote region of the Tibetan Plateau: implications for natural environmental response to human activities. Sci Total Environ 739:140087

Feng X, Wang Q, Sun Y, Zhang S, Wang F (2022) Microplastics change soil properties, heavy metal availability and bacterial community in a Pb-Zn-contaminated soil. J Hazard Mater 424:127364

Godoy V, Blázquez G, Calero M, Quesada L, Martín-Lara MA (2019) The potential of microplastics as carriers of metals. Environ Pollut 255:113363

Gui J, Sun Y, Wang J, Chen X, Zhang S, Wu D (2021) Microplastics in composting of rural domestic waste: abundance, characteristics, and release from the surface of macroplastics. Environ Pollut 274:116553

Guo JJ, Huang XP, Xiang L, Wang YZ, Li YW, Li H, Cai QY, Mo CH, Wong MH (2020) Source, migration and toxicology of microplastics in soil. Environ Int 137:105263

He P, Chen L, Shao L, Zhang H, Lü F (2019) Municipal solid waste (MSW) landfill: a source of microplastics? -evidence of microplastics in landfill leachate. Water Res 159:38–45

Hu X, Davies R, Morrissey K, Smith R, Fleming LE, Sharmina M, Clair RS, Hopkinson P (2022) Single-use plastic and COVID-19 in the NHS: barriers and opportunities. J Public Health Res 11(1)

Huang B, Sun L, Liu M, Huang H, He H, Han F, Wang X, Xu Z, Li B, Pan X (2021) Abundance and distribution characteristics of microplastic in plateau cultivated land of Yunnan Province, China. Environ Sci Pollut R 28:1675–1688

Huang Y, Liu Q, Jia W, Yan C, Wang J (2020) Agricultural plastic mulching as a source of microplastics in the terrestrial environment. Environ Pollut 260:114096

Huerta Lwanga E, Mendoza Vega J, Ku Quej V, Chi JDLA, Sanchez del Cid L, Chi C, Geissen V (2017) Field evidence for transfer of plastic debris along a terrestrial food chain. Sci Rep 7(1):1–7

Jiang X, Chen H, Liao Y, Ye Z, Li M, Klobučar G (2019) Ecotoxicity and genotoxicity of polystyrene microplastics on higher plant *Vicia faba*. Environ Pollut 250:831–838

Jin M, Wang X, Ren T, Wang J, Shan J (2021) Microplastics contamination in food and beverages: direct exposure to humans. J Food Sci 86(7):2816–2837

Khalid N, Aqeel M, Noman A (2020) Microplastics could be a threat to plants in terrestrial systems directly or indirectly. Environ Pollut 267:115653

Khalid N, Aqeel M, Noman A, Khan SM, Akhter N (2021) Interactions and effects of microplastics with heavy metals in aquatic and terrestrial environments. Environ Pollut 290:118104

Koelmans AA, Mohamed Nor NH, Hermsen E, Kooi M, Mintenig SM, De France J (2019) Microplastics in freshwaters and drinking water: critical review and assessment of data quality. Water Res 155:410–422

Lahive E, Walton A, Horton AA, Spurgeon DJ, Svendsen C (2019) Microplastic particles reduce reproduction in the terrestrial worm *Enchytraeus crypticus* in a soil exposure. Environ Pollut 255:113174

Leslie HA, Van Velzen MJ, Brandsma SH, Vethaak D, Garcia-Vallejo JJ, Lamoree MH (2022) Discovery and quantification of plastic particle pollution in human blood. Environ Int 107199

Liao Z, Ji X, Ma Y, Lv B, Huang W, Zhu X, Fang M, Wang Q, Wang X, Dahlgren R (2021) Airborne microplastics in indoor and outdoor environments of a coastal city in eastern China. J Hazard Mater 417:126007

Liu Y, Liu W, Yang X, Wang J, Lin H, Yang Y (2021) Microplastics are a hotspot for antibiotic resistance genes: progress and perspective. Sci Total Environ 773:145643

Loppi S, Roblin B, Paoli L, Aherne J (2021) Accumulation of airborne microplastics in lichens from a landfill dumping site (Italy). Sci Rep 11:4564

Lu L, Luo T, Zhao Y, Cai C, Fu Z, Jin Y (2019) Interaction between microplastics and microorganism as well as gut microbiota: a consideration on environmental animal and human health. Sci Total Environ 667:94–100

Ma W, Tai L, Qiao Z, Zhong L, Wang Z, Fu K, Chen G (2018) Contamination source apportionment and health risk assessment of heavy metals in soil around municipal solid waste incinerator: a case study in North China. Sci Total Environ 631:348–357

Natesan U, Vaikunth R, Kumar P, Ruthra R, Srinivasalu S (2021) Spatial distribution of microplastic concentration around landfill sites and its potential risk on groundwater. Chemosphere 277:130263

Ng EL, Lwanga EH, Eldridge SM, Johnston P, Hu HW, Geissen V, Chen D (2018) An overview of microplastic and nanoplastic pollution in agroecosystems. Sci Total Environ 627:1377–1388

Piehl S, Leibner A, Löder MG, Dris R, Bogner C, Laforsch C (2018) Identification and quantification of macro- and microplastics on an agricultural farmland. Sci Rep 8(1):17950

Ragoobur D, Huerta-Lwanga E, Somaroo GD (2021) Microplastics in agricultural soils, wastewater effluents and sewage sludge in Mauritius. Sci Total Environ 798:149326

Ragusa A, Svelato A, Santacroce C, Catalano P, Notarstefano V, Carnevali O, Giorgini E (2021) Plasticenta: first evidence of microplastics in human placenta. Environ Int 146:106274

Ren Z, Gui X, Xu X, Zhao L, Qiu H, Cao X (2021) Microplastics in the soil-groundwater environment: aging, migration, and co-transport of contaminants – a critical review. J Hazard Mater 419:126455

Rezaei M, Riksen MJ, Sirjani E, Sameni A, Geissen V (2019) Wind erosion as a driver for transport of light density microplastics. Sci Total Environ 669:273–281

Rillig MC (2012) Microplastic in terrestrial ecosystems and the soil? Environ Sci Technol 46:6453–6454

Roy P, Mohanty AK, Misra M (2022) Microplastics in ecosystems: their implications and mitigation pathways. Environmental Science: Advances 1(1):9–29

Sighicelli M, Pietrelli L, Lecce F, Iannilli V, Falconieri M, Coscia L, Di Vito S, Nuglio S, Zampetti G (2018) Microplastic pollution in the surface waters of Italian subalpine lakes. Environ Pollut 236:645–651

Sobhani Z, Al Amin M, Naidu R, Megharaj M, Fang C (2019) Identification and visualisation of microplastics by Raman mapping. Anal Chim Acta 1077:191–199

Thinh TQ, Sang TTN, Viet TQ, Dan NP, Strady E, Chung KLT (2020) Preliminary assessment on the microplastic contamination in the atmospheric fallout in the Phuoc Hiep landfill, Cu Chi, Ho Chi Minh city. Vietnam Journal of Science, Technology and Engineering 62(3):83–89

Thompson RC, Olsen Y, Mitchell RP, Davis A, Rowland SJ, John AW, McGonigle D, Russell AE (2004) Lost at sea: where is all the plastic? Science(Washington) 304: 838

Wang F, Zhang X, Zhang S, Zhang S, Sun Y (2020a) Interactions of microplastics and cadmium on plant growth and arbuscular mycorrhizal fungal communities in an agricultural soil. Chemosphere 254:126791

Wang J, Peng J, Tan Z, Gao Y, Zhan Z, Chen Q, Cai L (2017) Microplastics in the surface sediments from the Beijiang river littoral zone: composition, abundance, surface textures and interaction with heavy metals. Chemosphere 171:248–258

Wang J, Liu X, Li Y, Powell T, Wang X, Wang G, Zhang P (2019) Microplastics as contaminants in the soil environment: a mini-review. Sci Total Environ 691:848–857

Wang K, Chen W, Tian J, Niu F, Xing Y, Wu Y, Xu L (2022) Accumulation of microplastics in greenhouse soil after long-term plastic film mulching in Beijing. China Sci Total Environ 828:154544

Wang Q, Adams CA, Wang F, Sun Y, Zhang S (2021) Interactions between microplastics and soil fauna: a critical review. Crit Rev Env Sci Tec 1–33

Wang X, Li C, Liu K, Zhu L, Song Z, Li D (2020b) Atmospheric microplastic over the South China Sea and East Indian Ocean: abundance, distribution and source. J Hazard Mater 389:121846

Weithmann N, Möller JN, Löder MGJ, Piehl S, Laforsch C, Freitag R (2018) Organic fertilizer as a vehicle for the entry of microplastic into the environment. Sci Adv 4(4): eaap8060

Yan W, Hamid N, Deng S, Jia PP, Pei DS (2020) Individual and combined toxicogenetic effects of microplastics and heavy metals (Cd, Pb, and Zn) perturb gut microbiota homeostasis and gonadal development in marine medaka (*Oryzias melastigma*). J Hazard Mater 397:122795

Yang J, Li R, Zhou Q, Li L, Li Y, Tu C, Zhao X, Xiong K, Christie P, Luo Y (2021) Abundance and morphology of microplastics in an agricultural soil following long-term repeated application of pig manure. Environ Pollut 272:116028

Yu L, Zhang J, Liu Y, Chen L, Tao S, Liu W (2021) Distribution characteristics of microplastics in agricultural soils from the largest vegetable production base in China. Sci Total Environ 756:143860

Yu Q, Hu X, Yang B, Zhang G, Wang J, Ling W (2020a) Distribution, abundance and risks of microplastics in the environment. Chemosphere 249:126059

Yu Y, Chen H, Hua X, Dang Y, Han Y, Yu Z, Chen X, Ding P, Li H (2020b) Polystyrene microplastics (PS-MPs) toxicity induced oxidative stress and intestinal injury in nematode *Caenorhabditis elegans*. Sci Total Environ 726:138679

Zha F, Shang M, Ouyang Z, Guo X (2021) The aging behaviors and release of microplastics: a review. Gondwana Res

Zhang F, Man YB, Mo WY, Man KY, Wong MH (2020) Direct and indirect effects of microplastics on bivalves, with a focus on edible species: a mini-review. Crit Rev Env Sci Tec 50:2109–2143

Zhou B, Wang J, Zhang H, Shi H, Fei Y, Huang S, Tong Y, Wen D, Luo Y, Barceló D (2020a) Microplastics in agricultural soils on the coastal plain of Hangzhou Bay, East China: multiple sources other than plastic mulching film. J Hazard Mater 388:121814

Zhou Y, Liu X, Wang J (2019) Characterization of microplastics and the association of heavy metals with microplastics in suburban soil of central China. Sci Total Environ 694:133798

Zhou Y, Wang J, Zou M, Jia Z, Zhou S, Li Y (2020b) Microplastics in soils: a review of methods, occurrence, fate, transport, ecological and environmental risks. Sci Total Environ 748:141368

Zhu D, Ma J, Li G, Rillig MC, Zhu YG (2021) Soil plastispheres as hotspots of antibiotic resistance genes and potential pathogens. ISME J 16(2):521–532