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ORIGINAL PAPER

Comparison of Microplastic Characteristics in Mulched and Greenhouse Soils of a Major Agriculture Area, Korea

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Abstract

Soil microplastic (MP) contamination through plastic mulch and greenhouse soils is a global concern. However, whether plastic mulch contaminates the soil to a greater or lesser extent than the contamination caused by building greenhouses with MPs has not been documented. This study is the first to examine and compare the abundance and distribution of MPs in greenhouses and mulched soils of Korean agriculture field to obtain the polymer types and sizes of MPs present. The MP abundances in the greenhouse and mulched soils ranged from 50 to 379 and 158 to 943 particles kg^{-1}, respectively, with an average abundance of 221.4 and 356.8 particles kg^{-1}. No significant differences ($p > 0.05$) were observed in soil MP contamination between the greenhouse and mulching sites. At both sites, fragments (91%) were the predominant MP shape. MPs with a size < 300 μm were dominant, covering 99.57% of the mulch site and 99.69% of the greenhouse. Six MP polymers in the greenhouse and mulching sites: polypropylene, polyethylene, polyethylene terephthalate, polyvinyl chloride, polyethylene amide, and polymethyl methacrylate were identified. The soil MP contaminants in greenhouses and mulch sites in the Haean Basin have originated from the use of plastic films, and ropes. The first-hand data established by this study showed the same degree of MP contamination in mulch and greenhouse soils, which provides important background information on MP characteristics to understand the environmental behavior and ecological effects of MPs in soil systematically and comprehensively.

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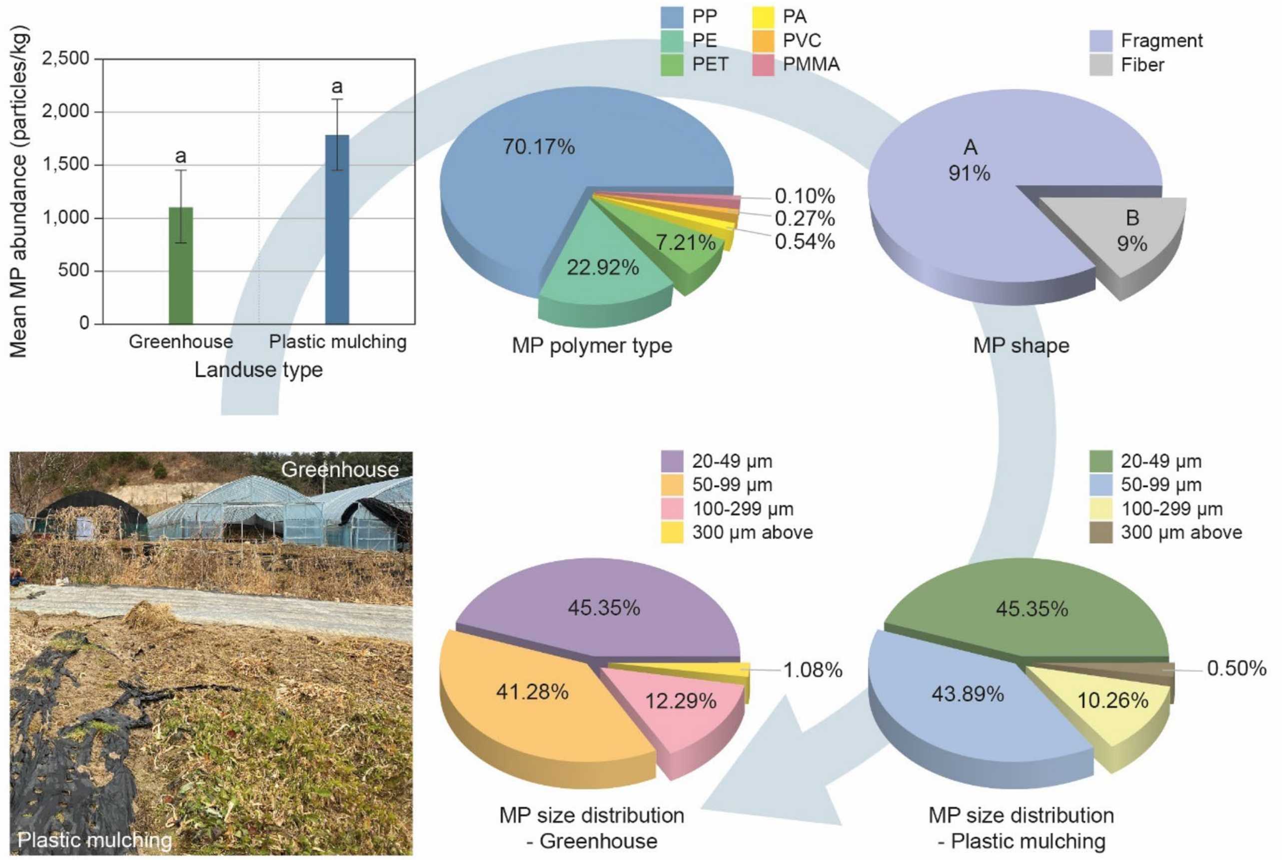
Graphical Abstract



Keywords Greenhouse contamination · Microplastics shape · Polymer type · Mulched soil · Polypropylene

Introduction

Since the Industrial Revolution that originated in Britain, the Earth has faced a series of challenges, such as global population explosion and overexploitation of soil [1–5]. Many people across the globe rely heavily on soil to produce food for their livelihoods [6–8]. Several studies have documented that over-exploitation of soils can lead to a shortage of arable land and a decline in soil fertility and moisture in the long run [9–11]. For instance, Nawaz et al. [12] reported that the continuously growing population of South Asia exerts a considerable amount of pressure on soils and degrades their fertility. To deal with the challenges arising from an excessive dependence on soils for agriculture, to feed the huge global population, tremendous efforts have been made to find alternatives that can help reduce the existing pressure on soils. In the search for a solution, the global scientific community has invented many technologies and materials to address this pressing concern.

In 1862, Alexander Parkes invented the first artificial plastic made from organic compounds to replace ivory and horn [13, 14]. In 1907, Dr. Leo Bakeland created plastic from an inorganic compound called cellulose [15, 16]. Since the invention of plastics, many technologies have been developed to help increase and/or enhance crop yields to feed the current large global population [17]. One such technology is the greenhouse. However, the long-term use of greenhouses built using plastic films may lead to soil microplastic (MP) contamination (< 5 mm). For example, Wang et al. [18] documented MP concentrations of approximately 2215.56 ± 1549.86 particles kg^{-1} in soils from an abandoned greenhouse and associated the high MP concentration with the high-intensity activity in the greenhouses used for crops that pollutes soils with MPs. In addition, Kim et al. [19] reported an average MP concentration of approximately 1880 ± 1563 particles kg^{-1} in soils from greenhouses in Korea. In Korea, greenhouses are often replaced after being used for three years or more [19].

Another technology that serves as a solution to ease soil degradation and help increase annual crop yields is plastic mulching. According to Wang et al., [20] plastic mulching is beneficial for increasing soil nutrient cycling and enzyme activity, and reducing soil moisture lost by evaporation. In Korea, plastic mulching is widely used to control weeds and grow crops such as ginseng, apples, and tomatoes, especially in cooler regions such as the Haean Basin, to increase crop yields; however plastic films are expected to be removed by law once crops are ready to be harvested [22]. Although plastic mulch is very useful in modern crop cultivation, many studies have reported that the long-term use of plastic mulch can contaminate soils with low MP concentrations. In addition, Haixin et al. [23] reported soil MP contamination concentrations as low as 384.6 particles kg^{-1} in plastic mulching farmland. In addition, Huang et al. [17] recorded a low MP concentration of approximately 1075.6 particles kg^{-1} in the soil after plastic mulching in cotton fields compared to the MP concentration reported at most greenhouse sites.

In contrast, some studies have reported MP concentrations in plastic mulching sites that are similar in magnitude to those reported in greenhouse sites. For example, Zhang et al. [24] documented MP concentrations of approximately 2840 particles kg^{-1} following tobacco cultivation with plastic mulching, which is nearly equal in magnitude to the MP concentrations in greenhouses. Meanwhile, several other studies have reported larger magnitudes of MP concentrations in plastic mulching soils compared to any of the magnitude of MPs reported in any studies to date. For example, Xu et al. [25] reported higher MP concentrations of 7183–10,586 particles kg^{-1} in a corn farm (*Zea mays L.*) with continuous plastic mulching. This MP concentration far exceeded that recorded in most greenhouse MP studies. Therefore, it is unclear whether mulched soil contaminates the soil more or less with MPs compared with building a greenhouse for growing crops in the same area. It is necessary to determine which of the two agricultural technologies is a lesser source of MPs to the soil. Knowing which of the two practices causes lesser soil contamination can help select a less toxic crop cultivation technology, as the use of both technologies cannot be cut off simultaneously because of their benefits for crop cultivation. To the best of our knowledge, most studies have not considered whether plastic mulched soils pollute soils with MPs to a greater or lesser extent than that caused by a greenhouse; therefore, the data from this study will fill the knowledge gap in this area of research interest. In this study, MP abundance and characteristics in mulched and greenhouse soils were investigated. It can be hypothesized that mulched and greenhouse soils have different MP abundances, polymer types, shapes, and sizes because of the differences in crop planting intensities and the removal of plastic film from mulch soils during crop harvesting stages. Therefore, this study aimed to (1) compare MP abundance between mulched and greenhouse soils and (2) explore MP size, shape, and polymer type in both mulched and greenhouse soils. To achieve this objective, soil samples were collected from both greenhouse and plastic mulching sites in the Haean Basin, an agriculturally dense area in the Republic of Korea. The results of this study will contribute to the prevention and mitigation of soil MP contamination and help to understand the distribution of MPs in greenhouses and mulch soils.

Materials and Methods

Site Description

The study was conducted at an adjacent plastic mulching and greenhouse site in the Haean Basin, approximately 110 km northeast of the capital of the Republic of Korea (hereafter Korea), Seoul (128°5′–128°11′E, 38°15′–38°20′N; Fig. 1) [26]. The Haean Basin has a temperate climate, with an average annual precipitation of approximately 1390 mm over the past 25 years, and an average annual temperature of approximately 13.4 °C for the same period [27]. A maximum rainfall of 350.0 mm was recorded in August, and the lowest was 49.8 mm in January (Fig. 2) [28]. The periphery of the Haean Basin is a Precambrian metamorphic complex comprising gneiss, schist, and quartzite. The interior of the basin is biotite granite that intruded into the Precambrian metamorphic complex in the Jurassic and overlying Quaternary alluvial unconformity [21, 27].

The topsoil of the Haean Basin is classified as a coarse soil texture that covers the finer-textured subsoil and underlying dense bedrock material [21]. Greenhouses in this area are commonly used to grow pepper, tomato, and watermelon (Table S1). Greenhouses are often recycled after a period of 5 years. According to Lee et al. [6], apple orchards and ginseng cultivation are increasing in the Haean Basin because of warm climatic changes in the southern part of the country. These orchards and ginseng fields use plastic mulch to increase yield [6]. In this area, plastic mulching was used for eight years before being replaced.

Soil Sample Collection

Topsoil samples (subsamples) were collected as triplicate soil cores at three different points (2 cm apart) within a quadratic area of 0.5×0.5 m^2 at five randomly selected plots within the greenhouse and plastic mulching sites to determine soil MP abundance, shape, and size distribution [Fig. 3; Table S1], [25, 29]. A stainless-steel ruler and soil

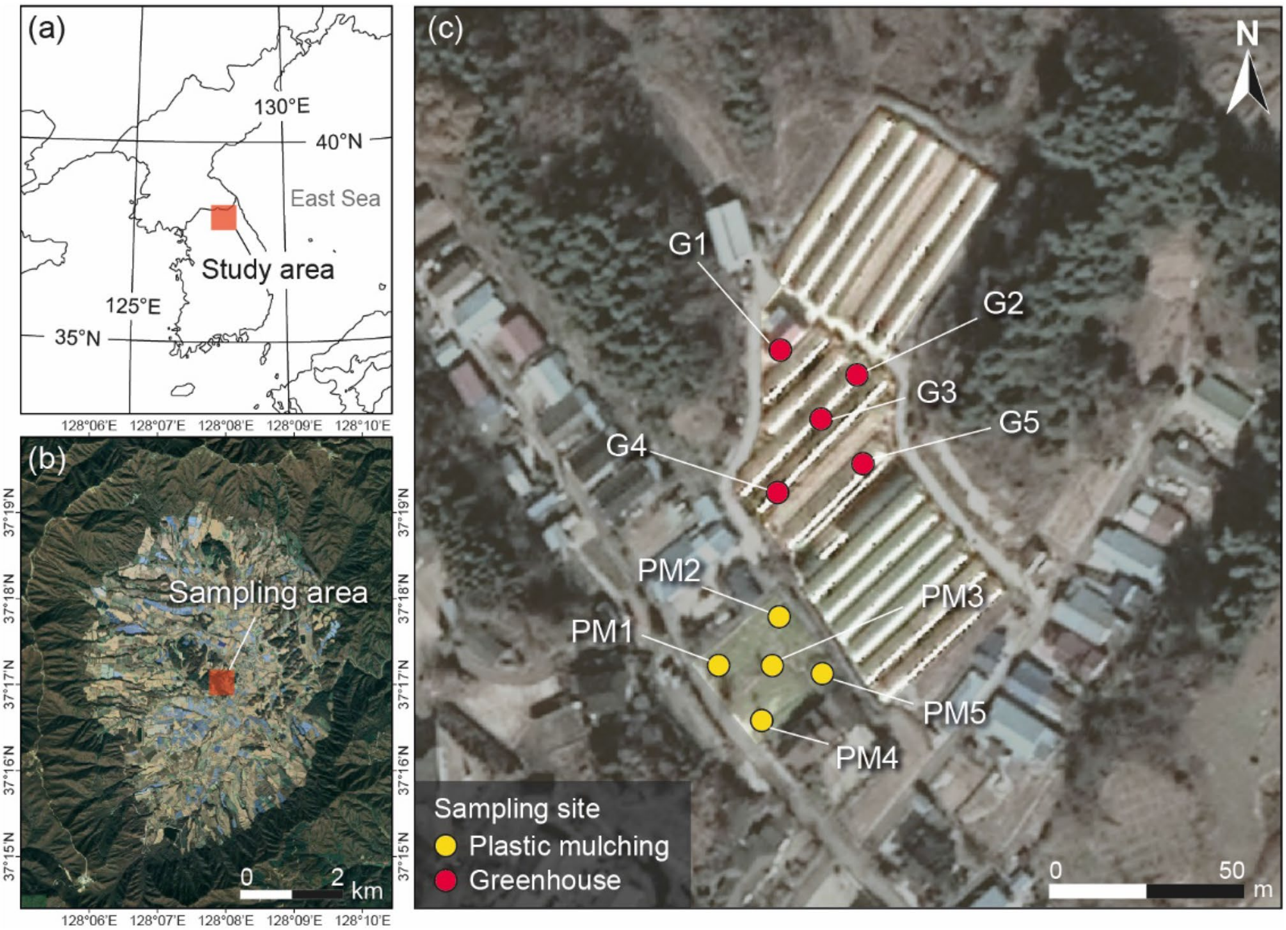


Fig. 1 Location of the (**a**)study area, (**b**) Haean basin, and (**c**)soil sampling points in the greenhouse (G = G1, G2, G3, G4, and G5) and plastic mulch area (PM = PM1, PM2, PM3, PM4, and PM5).

Fig. 2 Monthly mean air temperature and precipitation in the study area, Haean Basin from 1997 to 2022

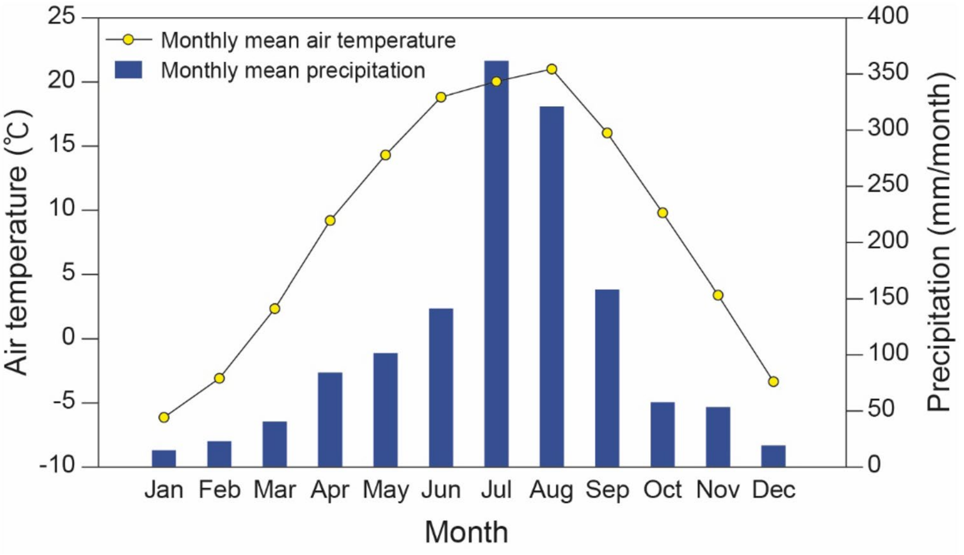


Fig. 3 Pictures showing the sampling site and some possible sources of MPs in the study area **(a)** a shattered plastic mulching film adjacent to the greenhouse site **(b)** plastic ropes used to support crops during growing and drying and plastic nets used to help dry crops in greenhouses after harvest **(c)** labeled glass vials used for composite soil samples after collection from the greenhouse site **(d)** external view of the greenhouse site where soil samples were collected

cores were used to set the topsoil at 0–10 cm to ensure accurate sampling at each site [30]. Triplicate samples (n = 3) collected from each point within each plot were mixed to form composite samples. After hand-picking any visible material, such as large stones, roots, leaves, and any unidentified litter, 5.0 kg of soil was stored in glass containers to avoid any plastic contamination before being transported to the laboratory (Fig. 3). After transportation, the soil samples were refrigerated at 4.0 °C until analysis [18]. In total, 30 soil samples (three subsamples (1.0 soil depth × 5.0 plots) × 2.0 land use sites) were collected from the plastic mulch and greenhouse sites selected for the study.

Microplastic Extraction

MPs in the soil were extracted and identified at the Korea Institute of Analytical Science and Technology in Seoul, Korea through a sequence of processes, as shown in Fig. 4. The soil samples were air-dried and crushed lightly using a rolling pestle. Soil samples were further filtered through a 5 mm stainless steel sieve to remove impurities, such as plant roots and leaves that could not be handpicked or were not clearly visible to the naked eye [17, 23, 31]. A 5 mm stainless steel mesh was chosen for this study because it met the MP definition, and a relatively small number of roots and leaves were visually observed in the soil samples in this study [32]. Soil (0.5 g) from each sampling point was mixed with 200 mL of 30% H_2O_2 in a beaker placed on a heating plate at 70 °C for approximately 72 h to completely digest and remove organic matter (Fig. 4).

Subsequently, the filtered soil samples were passed through a 20 µm stainless steel filter. The inorganic materials in the soil samples were extracted by density separation by mixing the soil samples with 40 mL of Li_2WO_4 solution (1.5 g cm^{-3}) for 24 h. In this study, Li_2WO_4 was used as the separation solution because of its high density, non-hazardous nature, ease of extraction of inorganic materials and high MP recovery rate [33, 34]. Precipitated inorganic particles were removed from the solution and the MP-containing supernatant was filtered through a 20.0 µm stainless steel filter. The filter was then placed in a desiccator and dried at room temperature (25.0 °C ± 1.2 °C). After drying, the filters

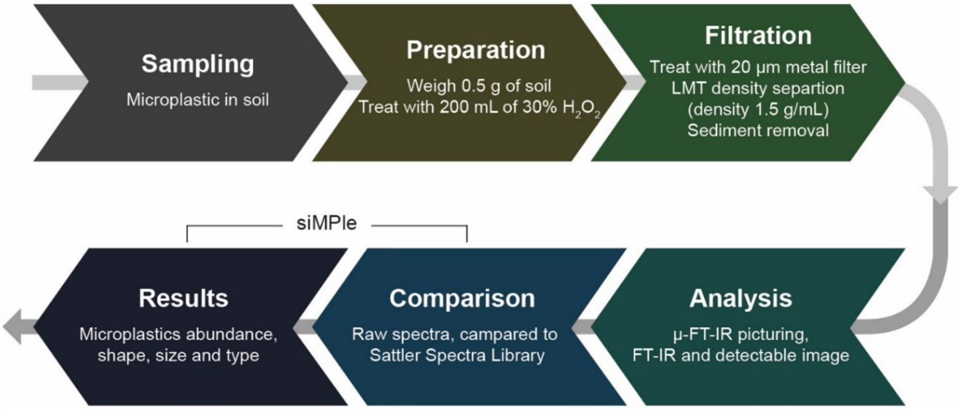


Fig. 4 Schematic diagram of soil microplastic extraction from collected soil samples

containing the MPs were placed in aluminum containers and covered with aluminum foil prior to identification.

Microplastic Identification

The filters containing the MPs were placed under a Fourier transform infrared (FT-IR) microscope to simultaneously count and identify MPs according to the method described by Bi et al. [35] and Zhang et al. [36]. FT-IR images with a spatial resolution of 5 µm were captured on 32 × 32 focal plane arrays. A scan spectral range of 4000– 650 cm^{-1} was set for 32 scans with an acquisition time of 3.0 s and a resolution of 5.0 cm^{-1}. FT-IR images were analyzed using the automated software MPs Finder (MPF; Purency or simple). The siMple software with a wavenumber range of 2420–2200 cm^{-1} was used to count the number of MPs (MP abundance) from each sample and provide comprehensive statistics on the size and polymer type on the filter according to the method described by Cunsolo et al. [37], Primpke et al. [38], and Uurasjärvi et al. [39]. The MPs were divided into the following size classes:20–49, 50–99, 100–299, and 300 µm and above. The composition of the MPs was identified from the infrared spectrum using a micro-Fourier transform interferometer (µ-FTIR, LUMOS II, Brucker, USA). The spectra were compared to the Sattler Spectra Library (purchased standard library), the matching rates were set at less than 60%, and the samples were considered as MP.

Quality Control and Assurance

Cotton and latex gloves were worn while collecting soil samples from the greenhouse and plastic mulching sites. In addition, during the extraction and identification of MPs, cotton laboratory coats and latex gloves were worn to protect soil samples from external MP sources, such as air and clothing. Distilled water was used to rinse the soil auger, stainless steel ruler, mortar and pestle (for crushing the soil), and glass used to store the soil.

In this study, triplicate blank samples were subjected to the same analytical procedure as the actual samples and MPs were not detected in these samples. Using the same method as above, the MP recovery rate was verified by spiking 300 µm PP and PE into 0.5 g of clean soil. The results showed that the recovery of MPs by Li_2WO_4 was 100%.

Statistical Analyses

Prior to the statistical analysis, the normality of the MPs datasets obtained from greenhouses and plastic mulching sites was checked separately using the Shapiro-Wilk test [29, 40]. Statistical differences in MP polymer type, size, and shape between the greenhouse and plastic mulching sites were checked using one-way analysis of variance (ANOVA) at the 5.0% significance level. In addition, the *t*-test was used to check for statistical differences in the mean values of MP abundance between the greenhouse and the plastic mulching site at a significance level of 5.0%.

Tukey's test was used for mean separation when ANOVA and *t*-test showed statistically significant differences ($p < 0.05$) [29]. The Kruskal-Wallis non-parametric test was used as a substitute test when the datasets did not follow the normality distribution rules; for example, the datasets for MP fibers and fragment shapes did not follow the normality distribution rules [41]. The software Past 4.10 (Systat Software Inc., Oyvind Hammer, Olso, Norway) was used to perform all statistical analyses, and the results are presented as mean values ± standard error.

Results

Microplastic Abundances

MPs were detected in each soil triumvirate sample collected at each sampling point at the greenhouses and plastic mulching sites (Fig. 5; Table S1). In this study, the total MP abundance in the soil of the greenhouse area was 1107

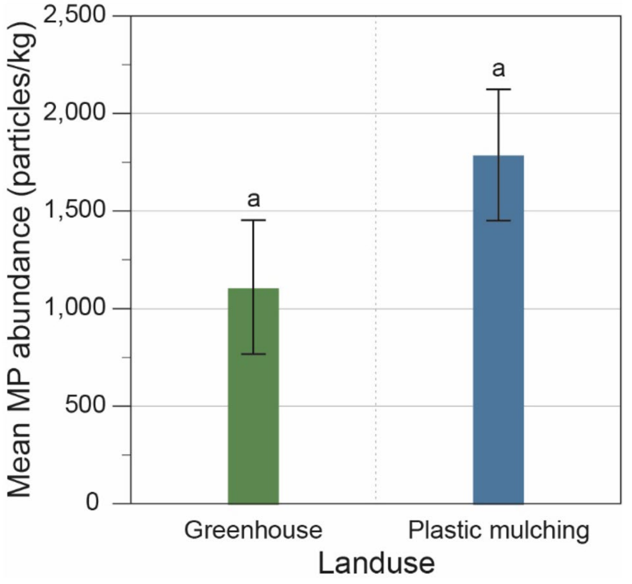


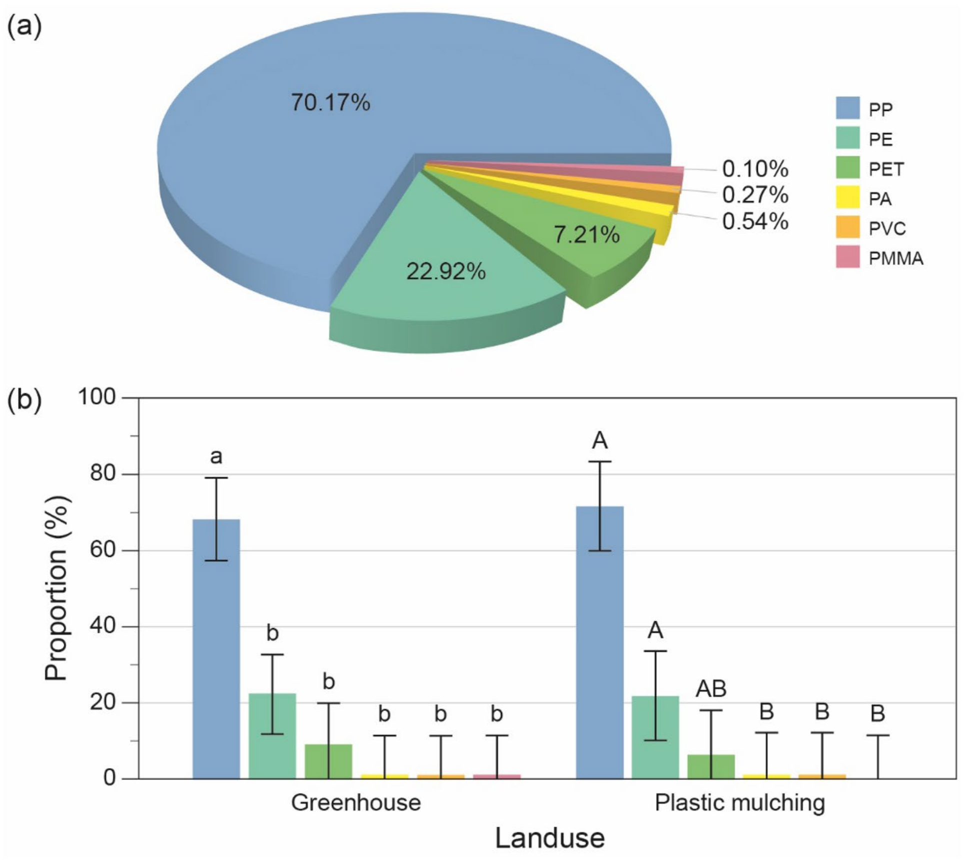
Fig. 5 Box plot of soil MP abundant (0–10 cm; particles kg^{-1}) in the greenhouse and plastic mulching area. Same lowercase (a, a) letter shows no statistical differences in MP abundances in greenhouse and plastic mulching site respectively

particles kg^{-1}, with an average abundance of 221.4 particles kg^{-1}, ranging from 50 to 383 particles kg^{-1}. At the plastic mulching site, the total MP abundance was 1748.0 particles kg^{-1}, within a range of 158 to 235 particles kg^{-1} and an average of abundance of 356.8 particles kg^{-1}. However, no significant differences were observed in soil MP abundance between the greenhouse and plastic mulching sites (Fig. 5; *t*-test, $p > 0.05$).

Microplastic Polymer Type

In this study, all MP ($n = 2855$) polymer types were identified using FTIR spectroscopy (Fig. 6a). A total of six variable types of MPs with a spectral match of > 60% were identified from all the soil samples collected from the plastic mulching and greenhouse sites. These MP polymer types were classified as polypropylene (PP), polyethylene (PE), polyethylene terephthalate (PET), polyvinyl chloride (PVC), polyethylene amide (PA), and polymethyl methacrylate (PMMA) (Fig. 6a). PP (70.17% of the total MPs identified) was perceived as the dominant MP polymer type, followed by PE (22.29%), and PET (7.21%). Among the six variable

Fig. 6 Soil MP polymer type (0–10 cm; particles Kg^{-1}) in the **(a)** overall study area, **(b)** greenhouse and plastic mulching site respectively. Different uppercase (A, B) or lowercase (a, b) letters show statistical differences in MP polymer types in the greenhouse and plastic mulching site respectively



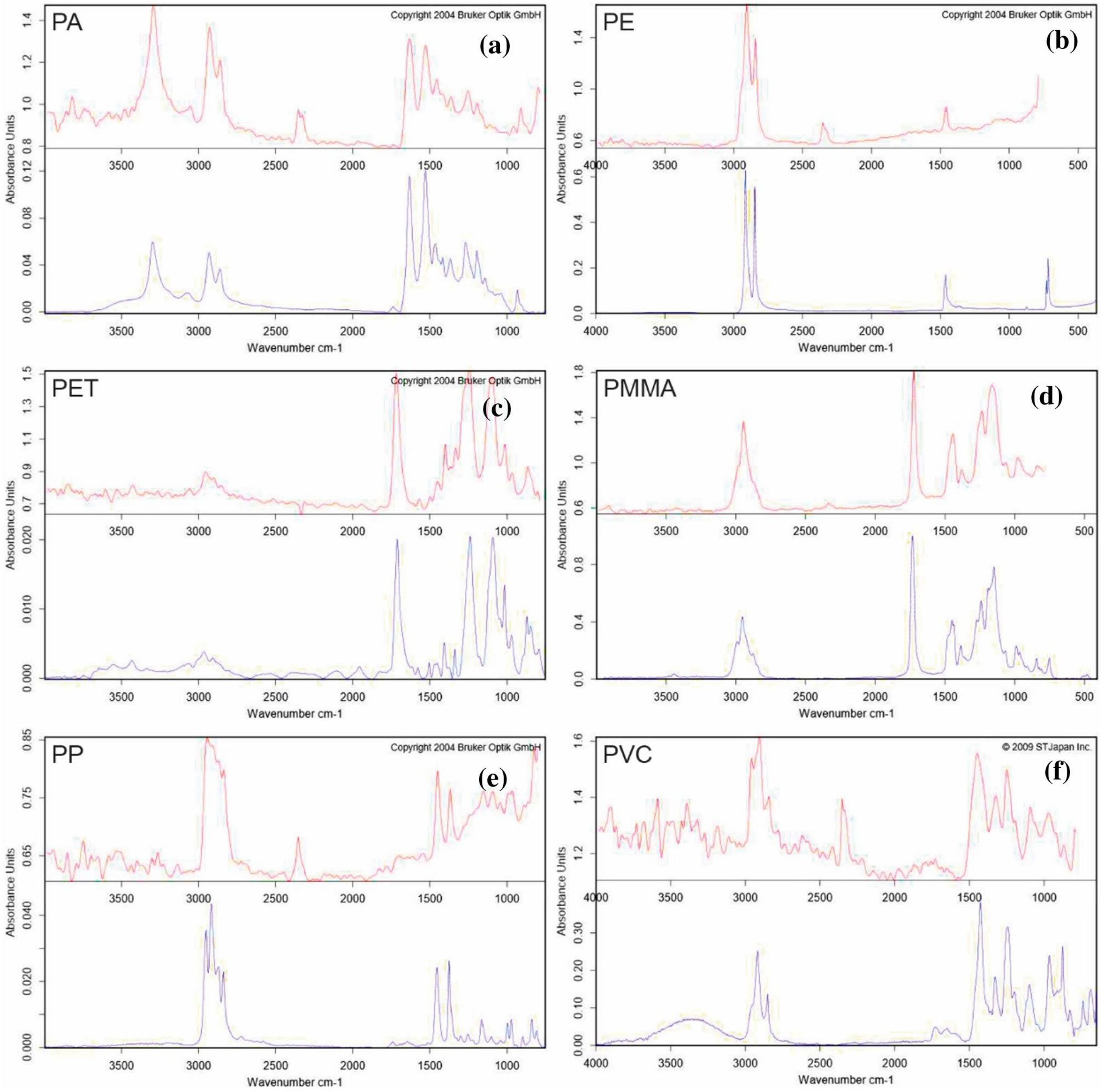


Fig. 7 FT-IR spectra of MPs from soil samples collected from the greenhouses compared to the reference polymers of (**a**) polyethylene, (**b**) polypropylene, (**c**) polystyrene, (**d**) poly(ethylene terephthalate, and (**e**) poly(vinyl chloride) (**f**) The comparison of the amount and composition of plastic debris

MP polymer types identified in soils in this study, PVC, PA, and PMMA were less than 1.0% (Fig. 6b).

At the greenhouse site, PP (68.02%) was the most significantly dominant MP polymer type; however, no significant difference was observed in MP abundance between PE (21.86%), PET (8.94%), PVC (0.36%), PA (0.54%), and PMMA (0.27%) ($p > 0.05$). In contrast, PP (71.44%) and PE (21.63%) were the dominant MP polymers ($p < 0.05$). However, there were no significant differences in the MP polymer abundances of PE (6.18%), PET (6.18%), PVC (0.21%), PA (0.53%), and PMMA (0.00%) ($p > 0.05$; Fig. 6b). The MP polymer types in both greenhouse and mulched soils were matched with the reference spectra, as shown in Figs. 7 and 8.

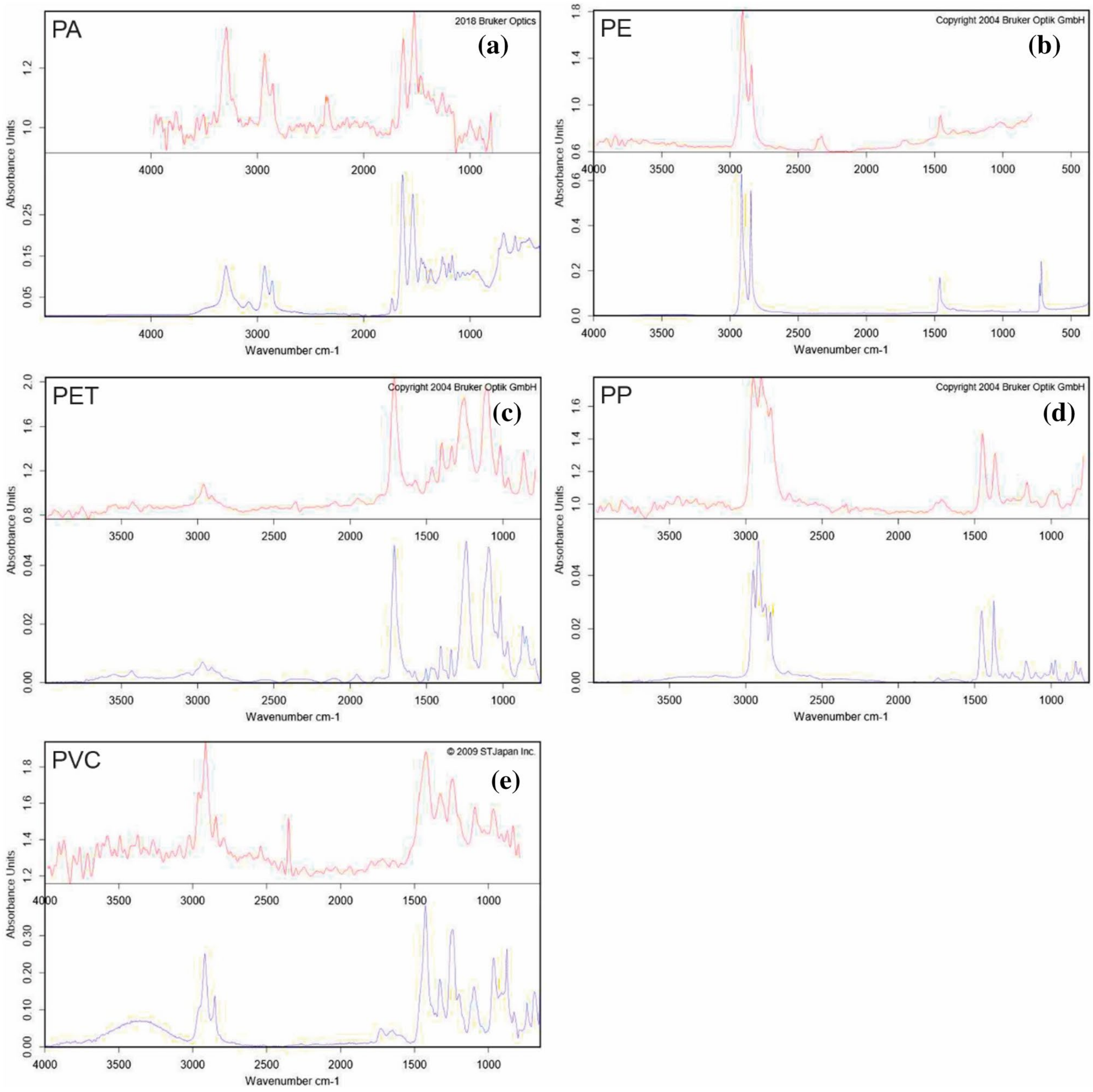


Fig. 8 FT-IR spectra of MPs from soil samples collected from the plastic mulched soil compared to the reference polymers of (**a**) polyethylene (PE), (**b**) polypropylene (PP), (**c**) polystyrene (PS), (**d**) poly(ethylene terephthalate) (PET), and (**e**) poly(vinyl chloride) (PVC). (**f**) The comparison of the amount and composition of plastic debris

Microplastic Shapes

In this study, two predominant MP shapes were identified in the greenhouses and plastic mulching sites, the majority of which were transparent or white (Figs. 9 and 10a). Of these MP shapes identified, the fragmented MP shape was observed as the major shape, accounting for 91.01% of the total (mean = 263.1 particles kg^{-1}). By contrast, fibrous MP types accounted for only 8.99% of the total MP shapes in the soil at the study site (mean = 260.0 particles kg^{-1}). Overall, fragmented MPs were present in significantly higher proportions than fibrous MPs [p (same med) = 0.0004328)] (Fig. 10a). Although the total number of fragmented MPs (approximately 58.22) at the plastic mulching site was numerically higher than that of fibrous MPs (3.49; $p = 0.05$), there was no significant difference ($p > 0.05$) between fibrous and fragmented MPs (approximately 5.50) in greenhouse soil ($p > 0.05$) (Fig. 10b).

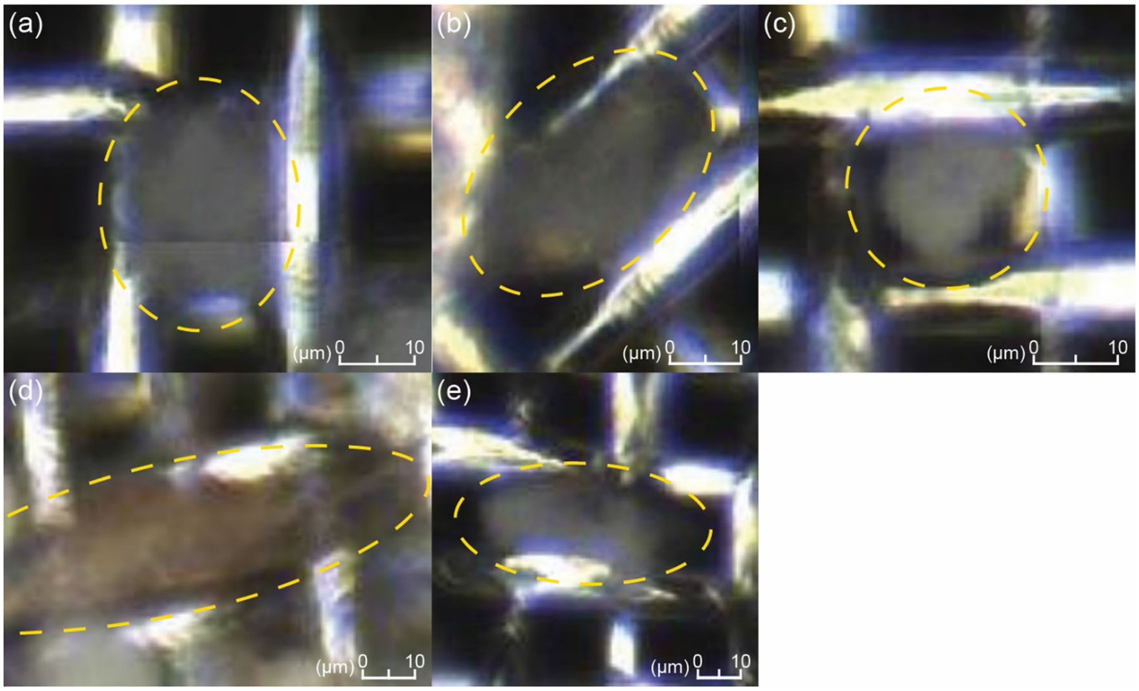
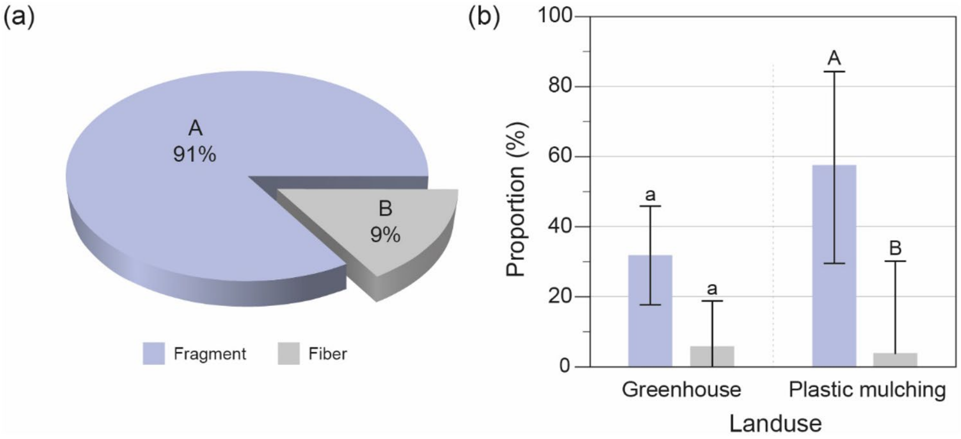


Fig. 9 **a** Polyvinyl Chloride fragment from 5G **b** Polypropylene fragment from 2PM **c** polypropylene fragment from 1PM **d** Polyethylene Terephthalate fiber from 2G **e** Polyethylene Terephthalate fiber from 5PM. Greenhouse (G = G2, and G5) and Plastic mulch area (PM = 2PM and 5PM).

Fig. 10 Soil MP shape (0–10 cm; particles kg^{-1}) in the (**a**) overall study area, (**b**) greenhouse and plastic mulching site respectively. Different uppercase (A, B) letters show statistical differences and same lowercase (a, a) letters display no statistical differences in MP shapes between the fragment and fiber MP shape



Microplastic Size

The MP size distribution for each soil sample is presented in Fig. 11. The MP size distribution for each soil sample collected from greenhouses and plastic mulching sites was divided into four categories:20–49, 50–99, 100–299, and 300 μm and above. Overall, MP sizes of 300 μm and above were detected and accounted for the smallest proportion of MP size distribution in the greenhouses and plastic mulching sites, at 0.42% and 0.311%, respectively. MP sizes of 20–299 μm in the greenhouse and the plastic mulching site accounted for 37.87% and 61.39%, respectively, which were significantly higher than those of MP sizes 300 μm, and above ($p < 0.05$). At the plastic mulching site, MP sizes of 20–49, 50–99, and 100–299 μm showed no significant difference ($p > 0.05$; Fig. 11). However, MPs of 20–299 μm occurred as a significantly higher proportion of soil MP contamination than MPs of 300 μm and above. In the greenhouse site, MPs of sizes 20–49, 50–99, and 100–299 μm were not significantly different; however, MPs of sizes 50–99, 300 μm, and above were significantly different at p (same mean) = 0.044.

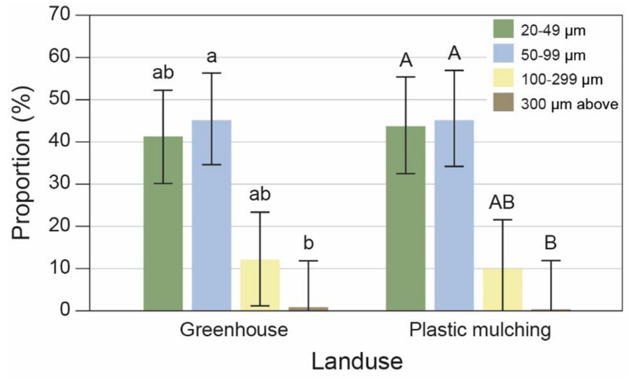


Fig. 11 MP size distribution (0–10 cm; µm) by sampling in a greenhouse and plastic mulching site. Different uppercase (A, B) and lowercase (a, b) letters show statistical differences in MP shapes in greenhouse and plastic mulching site respectively

Discussion

Sources of Microplastic Abundance in Mulch and Greenhouse Soils

The average MP concentration of 358.8 particles kg^{-1} determined in the mulching site of this study was lower than that of a cotton-plastic mulching site in Hangzhou Bay, China (571 particles kg^{-1}) [42] and a tobacco plastic mulching farm in Hubei, China (media = 647 particles kg^{-1}) [24]. The reason for the low concentration of MPs at the mulch site in this study is that the mulch site does not have any form of water irrigation [17]. For instance, according to Kim et al. [19], the water used for irrigation may be an additional source of soil MP pollution. In addition, Samandra et al. [43] reported that irrigation of soil with groundwater may be a source of MP pollution. Several studies have shown that the occasional use of organic or sludge fertilizers to treat soil is another source of MP contamination at plastic mulching sites [44]. However, no fertilization practices were used at the study site, suggesting that the MP concentrations were lower than those observed in other studies [24, 45]. For instance, Stefano et al. [46] reported macroplastic concentrations of approximately 9247 particles/mg in crop fields resulting from the application of organic and conventional fertilizers. These macroplastics can be degraded into MPs in the long run or by soil titling.

In addition, the lower average concentration of MPs (221.4 particles kg^{-1}) was observed in the greenhouse contrasts with the observations of a few other studies [e.g., Yanju, Korea [media = 379 particles kg^{-1}, [47], China: average = 5,124 ± 632 particles kg^{-1}], [48], where high concentrations of MPs were reported. The low average concentration of MPs from the greenhouse site suggests less intensive crop cultivation activity, short-term replacement of plastic films used for the construction of the greenhouse (5 years), and less human interference in the greenhouse compared to other study sites [44]. Despite different levels of soil MP contamination in greenhouses and mulched soils, there was no significant difference in soil MP concentration abundance between the two sites, as in the study by Liu et al. [49]. However, this contrasts with other studies that have reported significantly higher or lower abundances of MPs in plastic mulching soils than in greenhouse soils [19, 44, 49]. The lack of a significant difference in MP abundance between the plastic mulching and greenhouse sites is contrary to our conjecture that plastic mulching sites should have significantly higher MP abundance than greenhouse sites. In addition, a similar abundance of MPs between the two sites can be attributed to the fact that there were no planting activities in this study site, such as water irrigation or sludge application, which would lead to more MP pollution in the soil in a short period of time at the greenhouse site [49]. Plastic films used in greenhouse manufacturing are typically replaced after five years. In Korea, the plastic films used in plastic mulching and greenhouses should be removed after use [22].

Characteristics of Microplastic in Mulch and Greenhouse Soils

Overall, the dominance of the MP polymer PP in this study is consistent with the findings of previous studies [47, 50, 51]. According to Zhang et al. [24] and Xu et al. [25], the dominance of PP throughout the study site can be attributed to the fact that PP is one of the most widely used polymers for plastic films used in the construction of greenhouses and for plastic mulching. In greenhouse sites alone, the dominance of PP in the soil can be attributed to the fact that the weathered plastic films used to build the greenhouse undergo mechanical fragmentation, causing them to settle in the soil [51]. Also, the raw materials used to manufacture the ropes used to support plant growth within the greenhouse are made from PP [23].

Where plastic mulching is in place, the predominance of both PP and PE can be attributed to PE being a widely used polymer in farmlands since 1938 [52, 53]. Furthermore, the dominance of PE in plastic mulching fields suggests that plastic films made from PE polymers that are inadvertently discarded after crops are harvested easily degrade into MPs because of their thinness [23, 42, 48]. In addition, the dominance of PP may be related to soil contamination with MPs from unseen sources, such as MPs and/or atmospheric deposition from crop cultivation tools (e.g., ropes and machine parts used for farming) [25, 54].

This study determined fragment-shaped MPs as the dominant MP shape in the entire study area, which suggests physical and mechanical fragmentation of the plastic materials used either for plastic mulching or the construction of greenhouses [24, 55]. These results support those of previous studies that document fragment-shaped MPs as dominant MP shapes in greenhouse sites or plastic mulching sites [23, 30, 42, 56]. According to Wang et al. [18], the dominance of fragment-shaped MPs in soils from both sites suggests physical weathering by UV-radiation of plastic films used for plastic mulching, wear and tear of plastic films by soil particles, and weathering of abandoned plastic ropes used to support the growth of creeping plants in greenhouses. The lack of a significant difference in the proportion of fragment and fiber-shaped soil MPs in the greenhouse and plastic mulching sites could be discretely associated with the physical weathering of the plastic film used either for mulching or greenhouse construction [18].

In this study, MP sizes of 50–99 µm were dominant at the greenhouse site, which can be because towing to occasional tillage and soil abrasion, which facilitates the physical rupture of plastics deposited in the soils either involuntarily in the greenhouse site during soil preparation before planting or during harvesting [23, 57]. Likewise, at the plastic mulch site, the presence of a large number of MPs smaller than 300 µm may be owing to exposure of the plastic film used for mulching to UV radiation, weathering them to smaller sizes [30]. In addition, the predominance of MPs smaller than 300 µm may be related to the possibility of airborne MP deposition in the soil of the plastic mulching sites [53, 58–65].

Conclusion

In this study, the abundance of MP contaminants in greenhouses and plastic mulching topsoil in an agriculture-dominated region of Korea was examined and compared. Overall, soil MP abundance did not vary significantly between the greenhouse and plastic mulching sites. However, some MP polymer types, shapes, and sizes varied between plastic mulching and greenhouse sites. Furthermore, we observed that the dominant shape and size of MPs were fragments smaller than 300 µm in the plastic mulch and greenhouse sites. At the plastic mulching site, MPs made composed of PP and its copolymer PE were dominant. However, at the greenhouse site the dominant, PP was the dominant MP polymer. Following the discovery of MPs in plastic mulch and greenhouse sites, it can be inferred that the possible sources of these MPs are plastic films and plastic ropes. There was no significant difference in abundance between the two sites, suggesting that regardless of the form of plastic film used at the crop sites, they contaminate the soil with MPs in the long run. The results of this study undoubtedly show that both mulched and greenhouse soils are equal sources of MP pollution in crop fields, implying that these soils are significant environmental reservoirs of MPs. These results provide important background data that can be considered for future studies focusing on the sources of MPs and access to groundwater in the agricultural regions of Korea. These results can serve as a reference for reducing and controlling plastic mulch and soil MP pollution at greenhouse sites.

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Declarations

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.

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