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Greenhouse farming as a source of macroplastic and microplastics contamination in agricultural soils: a case study from Southeast-Hungary

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Abstract

Greenhouse plastic contaminations in agricultural soils were studied to quantify and examine the macroplastic and microplastic contaminants on the soil surface, soil profile, and groundwater under greenhouse farmland. Random sampling was used to select three areas in a greenhouse farm where macroplastic and microplastic data were collected. Four composite samples were collected from shallow (0–20 cm) and deep (20–40 cm) soils for each sampling point, respectively. Three soil profiles were dug, and samples were collected at intervals of 20 cm. Groundwater samples were also collected from the same profiles at a depth of 100 cm. Microplastics were extracted using predigestion of organic matter with 30% H_2O_2 and density separation with $ZnCl_2$. The total mass of macroplastics in the greenhouse farmland was 6.4 kg ha^{-1}. Polyethylene and polyvinyl chloride were the dominant plastic structures, and the dominant sizes were 1–5 and 0.5–1.0 cm, respectively. Overall, the average abundance of microplastics in the greenhouse soil was 225 ± 61.69 pieces/kg, and the dominant size structure was 2–3 mm. The average microplastic concentrations at depths of 0–20 and 20–40 cm were 300 ± 93 and 150.0 ± 76.3 pieces/kg, respectively. The average microplastic concentration in the groundwater was 2.3 pieces/l, and fibers were the dominant plastic structure. Given that microplastics were found in greenhouse soil, soil profiles, and groundwater, we recommend the careful cleaning and disposal of plastics on greenhouse farmland and further research to shed light on the level of microplastic contamination in the soil profiles and groundwater.

Keywords: greenhouse farming, macroplastic, microplastic, agricultural soil, pollution, groundwater

Abbreviations: MaP: Macroplastics; MiP: Microplastics; PE: Polyethylene; PET: Polyethylene terephthalate; PVC: Polyvinyl chloride; PP: Polypropylene.

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Introduction

Global plastic production has increased from 338 million tons in 2016 to 359 million tons in 2019 (PLASTIC EUROPE, 2019). Plastic has become a major consumable product in agriculture because of its cheapness, impermeability to precipitation and gases, malleability, lightweight, and ability to maintain a uniform soil temperature, transport fertilizer, and control weeds, disease, and pests (SUSANNA, 2018; PATEL & TANDEL, 2017; ANDRADY, 2003). In terms of plastic production, Asia, North America, and Europe dominate the world market. While Africa, Latin America, and the Commonwealth of Independent States countries also contribute to world production. China and Japan have experienced massive growth in the sector; thus, these countries now account for more than 30% of plastic production (PLASTIC EUROPE, 2019). In Europe, 3.4% of 51.2 million tons of the converted is used in protective cultivation, e.g., greenhouses, mulching, packaging, nurseries, and propagation (PLASTIC EUROPE, 2019).

The history of greenhouse farming began in 1953–1954 at the Kentucky Agricultural Experiment Station in the United States. Today, greenhouse farming contributes heavily to the production of various agricultural products (SAYADI-GMADA et al., 2019). Globally, greenhouse farming covers 220,000 ha of land and consumes 250,000–350,000 tons/year of plastic film (DILARA & BRIASSOULIS, 2000). For example, in Saudi Arabia, greenhouse farming covers 5,150 ha and produces 487,614 metric tons of vegetables (ALHAMDAN et al., 2009). Similarly, in the Almeria region of Spain, also referred to as the "plastic sea" more than 35,000 ha is used to produce 3,286,385 tons of horticultural products (SAYADI-GMADA et al., 2019; SUSANNA, 2018). In Hungary, greenhouse farming produces horticultural products and minimizes the need to import vegetables (NÉMETH & EHRET-BERCZI, 2014). Low-density polyethylene (LDPE) is the most common plastic used in greenhouse farming (BABAGHAYOU et al., 2020; ALHAMDAN et al., 2009; DILARA and BRIASSOULIS, 2000). Other plastics used in protective agriculture include polyvinyl chloride (PVC), ethylene-vinyl acetate, and linear LDPE.

Pollution with disposable plastic waste is a major challenge for municipalities, cities, and farmlands, and extensive use of plastic film in greenhouses has increased the amount of waste generated. Plastic contaminants can be large-sized particles, i.e. >5 mm, referred to as microplastics, or small-sized particles, i.e. <5 mm, referred to as microplastics. Microplastic waste can be transferred horizontally and vertically across and within the soil by wind, water, microorganisms, and leaching (O'CONNOR et al., 2019; REZAEI et al., 2019). Plastic contaminants in the soil ecosystem affect soil quality and fertility by altering its structure, bulk density, and water holding capacity (MBACHU et al., 2021). Furthermore, the quality of agricultural products and the growth and photosynthesis of plants are altered by the presence of microplastics (YANG et al., 2021). Importantly, microplastics can adsorb and transport contaminants such as heavy metals and other pollutants in the soil environment (CASTAN et al., 2021,). Lastly, direct ingestion of microplastics or consumption through contaminated food, such as fish and agricultural products, is a threat to human health (MO et al., 2021). Recent studies have also confirmed the presence of microplastic contamination in groundwater (SU et al., 2021; MORA et al., 2021).

Studies on macroplastics in agricultural soil and the characteristics of macro contaminants have rarely been conducted, contrary to the number of studies on microplastics. Nevertheless, studies on macroplastics are necessary because they become a source of microplastics when they fragment. Hence, improving our understanding of macroplastics will also provide new insights into microplastics. As previously stated, greenhouse farming generates plastic waste in large quantities (ISARI et al., 2021; SUSANNA, 2018), most of which is typically disposed of by burning, uncontrolled scattering in fields, or removal to unauthorized dumping sites (DILARA & BRIASSOULIS, 2000). Soil microplastic pollution from sources such as mulching (MENG et al., 2021), sewage sludge (CORRADINI et al., 2019), and organic and inorganic fertilizer application (BERIOT et al., 2021; KATSUMI et al., 2020) has recently been studied, as have forest, residential, and traffic soils (CHOI et al., 2020). However, the contribution of greenhouse farming to plastic contamination in agricultural farmlands is understudied despite the massive contribution of this farming practice to plastic contamination in agricultural soils (ISARI et al., 2021; SUSANNA, 2018). Moreover, there is a knowledge gap in microplastic contamination in the soil profiles and groundwater of agricultural and general soils. Recently, the WHO lamented the lack of studies on microplastics in drinking water; they emphasized that although the scant data do not reveal the threat to human health, there is a need to collect more data to draw proper conclusions. Hence, the present case study aimed (1) to quantify the level of macroplastics and microplastics in the greenhouse farmlands of Southeast Hungary; (2) to examine the types and morphological structures of these plastics in these greenhouse farmlands; and (3) to evaluate microplastic distribution and contamination in the soil profiles and groundwater of this greenhouse farmland, respectively.

Materials and Methods

Study site

This research was conducted on soils used for greenhouse cultivation and conventional farmlands (*Figure 1*). The study areas are located next to Szeged in the south-eastern part of Hungary (N 46.28990, E 20.18043). The climatic conditions are warm and dry (mean annual temperature: 10.5°C; mean annual precipitation: 520 mm), with 2,080–2,090 h per annum average annual radiation. The area is 84 m above sea level, and the perched groundwater depth is 100 cm. The sample area is plain with loess bedrock, and the natural soil type is Phaeozem (according to the World Reference Base for Soil Resources) (SZOLNOKI et al., 2013). The greenhouse area was an abandoned site of the area. It was established in the 1990s and has been abandoned since 2015. The area was used for tomatoes cultivation, whereas the conventional (control) site was used to grow numerous crops (mainly wheat). Both areas were selected based on size, history, identical soil type and proximity. Sampling occurred in March 2021. In total, 36 soil samples were collected, of which 12 were from the greenhouse farmland (at depths of 0–20 and 20–40 cm), 20 were from the greenhouse soil profile, and 4 were from the control. Additionally, three shallow groundwater samples (160, 120, 120 cm depths) were collected from the greenhouse farmland.

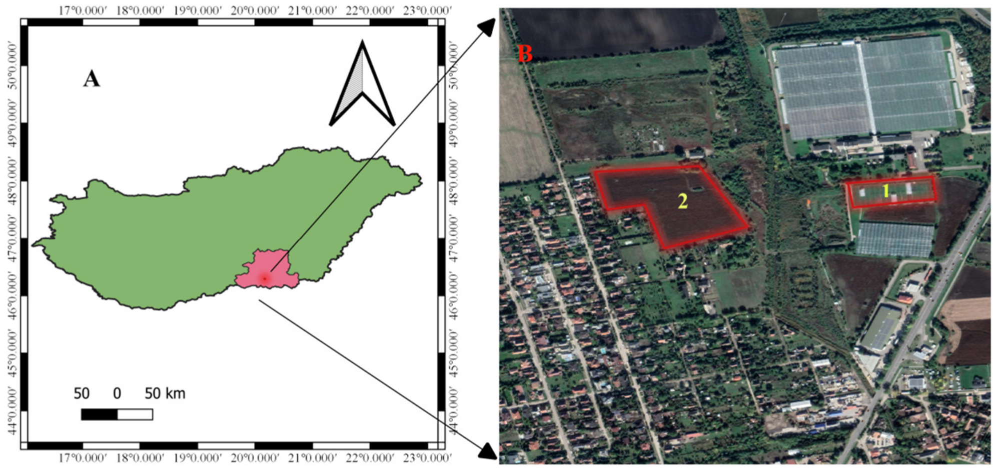

Figure 1
Study area. (A) Map of Hungary showing the location of the study area. (B) Satellite image showing (1) the greenhouse farmland and (2) the conventional farmland (control site).

Collection of composite samples from the topsoil for macroplastic and microplastic quantity determination

The greenhouse farmland was divided into 15 areas, each sized 52×9 m. Three areas were randomly selected, and the visible macroplastic debris on the surface was carefully picked and collected by two separate observers who walked through the areas. All collected plastic particles were precleaned to remove the attached soil materials and stored in large polyethylene (PE) plastic bags, after which they were transferred to the laboratory for further analysis. By contrast, a metallic auger, tape, hand shovel, water level meter and buckets were used to collect microplastic samples from the greenhouse and conventional farmlands. The three selected areas of greenhouse farmland were equally divided into two parts. In each part, the soil layer was divided into two layers (0–20 and 20–40 cm). Four samples from each layer were pooled, homogenized and comprised a composite sample; hence, 12 samples were collected. The same method was used for control sampling and 4 samples were collected. In total, 16 soil samples were collected from the soil surface of both greenhouse farmland and control. The samples were first covered with aluminum foil before being stored in bags and transferred to the laboratory for further analysis.

Sampling from the soil profiles and groundwater

In the middle of each sampling plot that was used for macroplastic collection three boreholes were drilled into the greenhouse farmland to collect samples from the soil profile and groundwater. Profile samples were obtained at 20 cm intervals from the surface to the layer where the groundwater was reached; the three profiles had depths of 160, 140, and 140 cm, respectively. Water samples were collected in 1 l plastic bottles and stored in a fridge at 4°C before analysis.

Macroplastic sample preparation

Macroplastic materials were wholly submerged in buckets containing tap water, soaked for 48 h to remove all impurities and attached soils. The plastics were then gently washed, and the waters were passed through a 5 mm sieve. The larger and retained plastic materials were dried for 4 days at room temperature. Subsequently, the plastics were separated, counted, and measured using a ruler in polymer type and particle size. An electric analytical balance was used to weigh the plastics. For particle size categorization, the following classes were used: 0.5–1.0, 1–5, 5–10, 10–15 and >15 cm.

Microplastic sample preparation and extraction

To obtain pure plastic debris, a method developed by LI et al. (2019) was modified and used. Briefly, the soils were oven-dried at 40°C, gently grinded into smaller pieces and sieved with a 5 mm sieve. In 250 ml conical flasks, 10 g of soil was mixed with 40 ml of 30% H_2O_2 and 10 ml of Fenton reagent for organic matter digestion. The solutions were heated at 70°C until they had dried up. The flask containers were then immersed in cold water and a few drops of butyl alcohol were added to reduce the samples spout out. $ZnCl_2$ [1.5 g cm^{-3} (5 mol l^{-1})] was used as a flotation salt and 40 ml of the solution was added. The complete solutions were capped with aluminum foil and shaken for 1 h at 200 rpm in an orbital shaker, after which they were emptied into 100 ml beakers and allowed to settle for 24 h. Approximately 20 ml of the upper supernatants were collected with a glass pipette and 20 ml of $ZnCl_2$ was added to the solution, which was shaken for 30 min in the orbital shaker for a second time. The upper supernatants were again collected and combined with the first supernatants to form single microplastic extracts. These extracts were later filtered through a nylon membrane filter (20 µm) and Whatman filter (0.45 µm), respectively, using a vacuum pump. The filters were air-dried and taken to the laboratory for microscopic microplastic identification and quantification. For groundwater analysis, samples were filtered through a Whatman filter (0.45 µm) by the aid of vacuum pump. The filters were placed in Petri dishes and covered with aluminum foil, dried at room temperature and examined with an Inspex II microscope. The suspected plastic particles (from the soil and groundwater) were confirmed using a needle and heat method and later Raman spectroscopic analysis.

Identification, classification, and quantification of plastics

The extracted microplastics were observed using an Inspex II microscope (software version: 1.06; film ware version: F001-001-011; ring light version: 1.03; Ireland) at 50× magnification. Some suspected microplastic particles were confirmed using the heat and needle method. These experiments were conducted at the analytical laboratory of the Department of Geoinformatics, Physical and

Environmental Geography, University of Szeged. Pieces of different macroplastics and 10% of the suspected microplastics were later confirmed using a Raman spectrometer. Obtained Raman spectra were compared with the Raman library; thus, the compositions of plastic materials were accurately determined. Raman analysis was performed at the Department of Mineralogy, Geochemistry and Petrology, University of Szeged.

Statistical analysis and quality control

Both descriptive and inferential statistics were used in our analyses. Descriptive statistical analysis was performed using Microsoft Excel, whereas inferential analysis was conducted using SPSS (version 22). Differences in the number of microplastics among soil depths were determined using a simple Student t-test. The relationship between microplastics and soil depth was determined using 'Spearman's rank correlation. ANOVA was used to determine the relationships among soil profiles. A bare minimum of plastic materials was used during sampling and laboratory analysis. Contamination prevention techniques, such as cleaning the auger before the next sampling in the field and avoiding samples mix, were strictly ensured in the field. Similarly, rinsing the apparatus with distilled water three times was adopted throughout the laboratory processes, during which researchers always wore a cotton lab coat and hand gloves. Aluminum foil was used from sampling until the final stages to cover the analyzed samples to prevent atmospheric contamination.

Result and discussion

Abundance and characteristics of macroplastics on the greenhouse soil

Macroplastic residues were found in all sampled areas of the greenhouse farmlands. The total mass of macroplastics was 6.4 kg ha^{-1} for the entire farmland, most of which were agro-related plastics, including films from ruined greenhouse covers, fragments of pipe from polyvinyl chloride (PVC) and plastic fiber strings that were likely used for tightening the greenhouse structure. These contaminant materials are believed to have come from the use of agricultural equipment; hence, they are agricultural plastics. Nonagricultural plastics were also found in the area, including candy wrappers, plastic bottles and particles from other materials presumed to have appeared in the area due to human activities and other environmental sources (e.g., carried by the wind). *Figure 2* shows the size distribution of macroplastics; in descending order, the distribution was as follows: 1–5 cm (46.31%), 0.5–1.0 cm (19.70%), >15 cm (18.71%), 5–10 cm (9.85%), and 10–15 cm (5.43%). The macroplastic size distribution according to weight was as follows: >15 cm [219 g (4679 g ha^{-1})]; 5–10 cm [37 g (790 g ha^{-1})], 10–15 cm [23 g (491 g ha^{-1})], 1–5 cm [19 g (405 g ha^{-1})], and 0.5–1.0 cm [0.62 g (13 g ha^{-1})]. This result is consistent with previous studies on the presence of mesoplastics and microplastics in agricultural soils from greenhouse, horticulture and mulch farmlands (CHOI et al., 2020; MENG et al., 2020; HUANG et al., 2020; RAMOS et al., 2015). In other respect, our result is inconsistent with those of earlier studies because lower macroplastic content was found. This may have been due to the duration of plastic film application on the farmlands or mulch plastic having a greater chance of remaining in the soil than greenhouse plastic because the former directly contact agricultural soil. Nevertheless, the current quantitative data show the stages of macroplastic fragmentation into smaller pieces (microplastics) in the greenhouse farmlands due to aging caused by single or multiple effects such as agrochemicals, environmental pressure, thickness, content of the plastic films and climatic conditions (BABAGHAYOU et al., 2020).

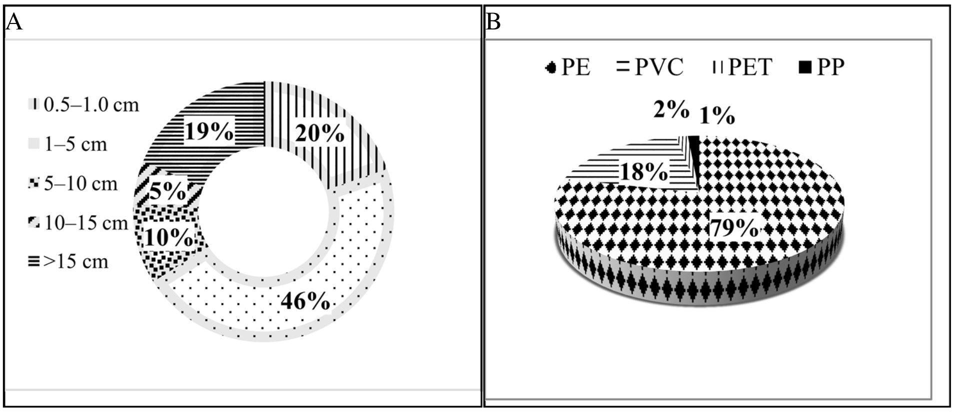

Figure 2
Size and polymer type of macroplastics, (A) Size of the macroplastics on soil surface, percentages indicate the number of macroplastic pieces. (B) Polymertypes, PE, polyethylene; PVC, polyvinyl chloride; PET, polyethylene terephthalate; and PP, polypropylene.

Figure 2 also shows the polymer types detected in terms of their weight. The identified polymers were polyethylene (PE), polyvinyl chloride (PVC), polyethylene terephthalate (PET), and polypropylene (PP). PE was dominant (79%) followed by PVC (18%), PET (2%), and PP (1%). PE and PVC as dominant polymers occurred because of their extensive use in plastic film coverage and water pipes, respectively (DILARA & BRIASSOULIS, 2000). These findings agree with those of an earlier study, in which PE was the most often used plastic and generated plastic waste in Almeria, Spain (SAYADI-GMADA et al., 2019). PET and PP wastes are likely to originate from, for example, the remains of plastic fiber strings, plastic bottles and single-use cups.

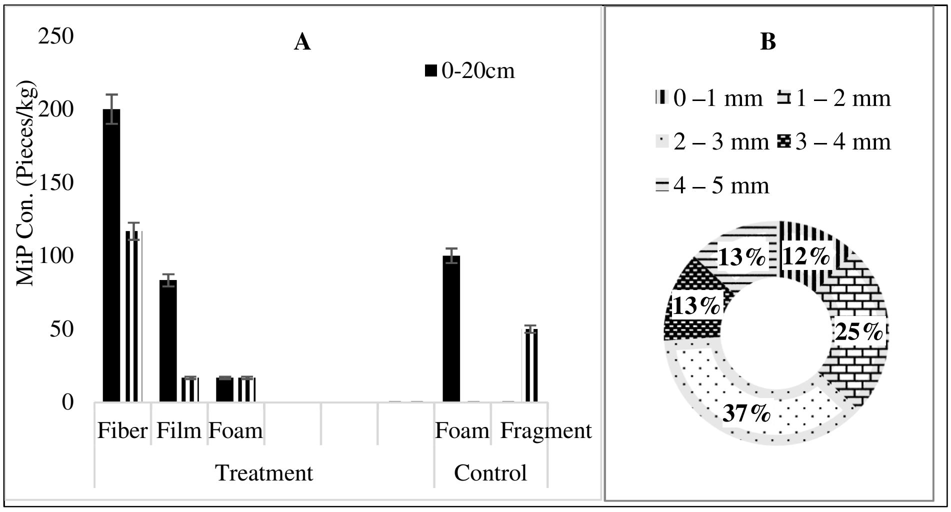

Figure 3
(A) structure of microplastics (MiP) in the soil of greenhouse and control farmland at different soil depths. (B) size of microplastics collected in the greenhouse farmland.

Abundance and characteristics of microplastics in greenhouse topsoil according to the analysis of composite samples

Microplastics were found at most sampling points and soil depths in greenhouse farmlands. Overall, the average microplastic contamination (of two depths) was 225 ± 61.69 pieces/kg (mean ± standard error). The amount varied across sampling points. The average microplastic contents at soil depths of 0–20 and 20–40 cm were 300 ± 93.09 and 150 ± 76.37 pieces/kg, respectively. Hence, microplastic content was higher in the surface layer than in the deeper layer (*Figure 3*); however, the difference was not significant (independent t-test: $P > 0.05$). The highest microplastic content recorded in the area was 500 pieces/kg, which agrees with the limited number of similar studies on microplastic concentrations in greenhouse soils, e.g., ISARI et al. (2021) recorded 30 1 and 69 items/kg in the greenhouse soils of watermelon and tomatoes, respectively, in Ilia County, Western Greece. CHOI et al. (2020) found an average of 755 pieces/kg in the greenhouse soils of Yeoju, Republic of Korea, whereas LI et al. (2021) found 1,300–3,400 pieces/kg in the greenhouse soils of China. Additionally, RAMOS et al. (2015) concluded that small pieces of PE mulch film plastics were abundant in the horticultural soils of peri-urban Argentina. The abundance of microplastics in the present study was lower than that reported in previous studies; this might have occurred because of the low microplastic content in the groundwater (*Figure 4*), which is used for irrigation water; this might also be due to the policy of banning sludge application in the greenhouse farmlands in the study area as previous studies such as CORRADINI et al. (2019) confirm that sewage sludge application increases the level of microplastics contaminants in the agricultural soil. Other reasons for the discrepancy might include general differences in the study areas, land clearing processes and management, and the duration of greenhouse and mulch practices. The present study's penetration of microplastics at various soil depths supports other studies that have shown microplastic penetration at different soil depths from 0 to 40 cm (HUANG et al., 2020; MENG et al., 2020). Moreover, microplastic penetration is a potential threat to soil profile and groundwater safety because recent findings confirm the abundance of contaminants in groundwater and aquifers (MORA et al., 2021).

The greenhouse soils samples were found to have considerable differences compared with conventional farmland samples (control). There were disparities in the number of microplastics extracted and the microplastic structures. For example, 2,700 pieces/kg with an average of 225 pieces/kg was recorded in greenhouse soil samples (0–20 and 20–40 cm), whereas only 300 pieces/kg with an average of 75 pieces/kg were found in four control samples (*Figure 3*). Structurally, microplastic fibers, film and foams were extracted from the greenhouse soils, whereas fragments and foam were extracted from the control. The presence of other plastic structures besides plastic films, such as fibers and foam, in the greenhouse farmland maybe due to irrigation water, the type of fertilizer applied, atmospheric deposition, wind and surface runoff. These findings support previous studies that found greenhouse farming to be a source of microplastics in agricultural soils (ISARI et al., 2021; SUSANNA, 2018). The abundance of microplastics in the control site, even in small quantities, shows the ubiquitous nature and distribution of microplastics in all parts of the environment.

Abundance of microplastics in soil profiles

Three profiles were intensively studied to determine the abundance of microplastics in different soil layers (Figure 4). One-way ANOVA revealed that there were no significant differences among the three profiles in terms of microplastic availability in the soil horizon [$F(2, 17) = 0.49$, $P > 0.05$]. Individual profile analysis of profile 1 (*Figure 4 A and D*) revealed five hundred microplastics in 8 kg samples taken from the soil horizon. The distribution of these plastic particles was not uniform: the first layers did not contain microplastics, whereas the 100–120 cm layer contained two hundred pieces/kg, and one hundred pieces/kg was found in each 40–60, 120–140, and 140–160 cm layers, respectively. According to Spearman's correlation analysis, there was a moderate positive correlation between depth and microplastic content in this profile, but it was not statistically significant [$r(8) = 0.626$, $P = 0.097$]. In profile 2, seven hundred microplastics were recorded in 6 kg from the soil horizon (*Figure 4 B*) with the following distribution: three hundred pieces/kg g in the 80–100 cm horizon, two hundred pieces/kg in the 0–20 cm horizon, one hundred pieces/kg in each of the 20–40 and 60–80 layers, and zero pieces/kg microplastics in the 40–60 and 100–120 cm layers. A weak negative correlation was not statistically significant between depth and microplastic content [Spearman's correlation: $r(6) = -0.235$, $P = 0.653$]. In profile 3, six hundred microplastics were recorded in 6 kg from the soil horizon (*Figure 4C*). Three hundred pieces/kg were recorded in the 40–60 cm layer, two hundred pieces/kg in the 0–20cm layer, one hundred pieces/kg in the 20–40 cm layer, and zero pieces/kg in the 60–80, 80–100, and 100–120 cm layers, respectively. A strong negative correlation between depth and microplastic content was not statistically significant [r (6) = −0.759, P = 0.080]. The number of MiP in the soil surface (0–40 cm) is higher than the number of MiP found in the soil profiles. This occurred because of the differences in the sampling techniques as composite sampling was carried out for soil surface and grab sampling was carried out for soil profiles.

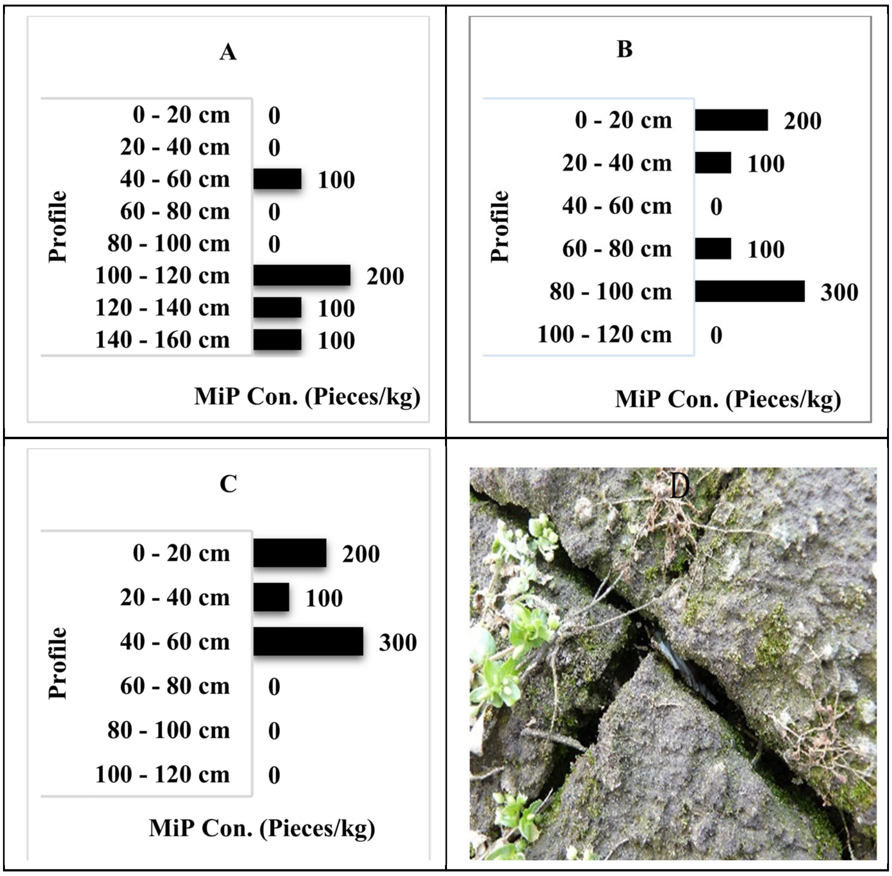

Figure 4
Microplastics concentration (MiP Con.) in the soil profiles. (A) Profile 1, (B) Profile 2, and (C) Profile 3. (D) Photographic image of plastic debris on the soil surface and in its cracks

These results agree with previous findings on the penetration of microplastics at different soil depths from 0 to 80 cm (CAO et al., 2021). Moreover, the vertical distribution of soil microplastics from the surface to the soil horizon occurred as a result of soil texture, the dry–wet nature of the soil, agricultural activities (e.g. plowing and harrowing), leaching of irrigation water, and transportation of microplastics by soil microorganisms through their various activities (CAO et al., 2021; O'CONNOR et al., 2019). Overall, these findings imply that the presence of microplastics deep in the soil could contaminate underground and soil aquifers over time.

Abundance of microplastics in groundwater

To access groundwater, three areas were drilled at the greenhouse farmlands. Drilling 1 had a depth of 160 cm, and water was collected at a restful depth of 100 cm after a waiting period of 40 min. Drilling 2 had a depth of 120 cm, and water was collected at a restful depth of 100 cm after a waiting period of 22 min. Lastly, drilling 3 had a depth of 120 cm, and water was collected at a restful depth of 100 cm after a waiting period of 17 min (*Table 1*). Microplastics were recorded in two of the three drilled areas (not in Drilling 3). The average concentration of microplastics in the groundwater was 2.3 pieces/L. In Drilling 2, the highest number of microplastics recorded was five particles, whereas that in Drilling 1 was three particles. These results are consistent with the limited previous findings on groundwater status. For example, SU et al. (2021) found a few microplastic fibers in the Jiaodong Peninsula, China, and PANNO et al. (2019) reported 15.3 particles/l in karst groundwater. Our results also support the hypothesis of WANNER (2021), who assumed that deposition of plastics in agricultural areas could contaminate the groundwater and soil aquifers beneath agricultural farmlands. However, our finding differs from that of PANNO et al. (2019) in terms of the wide gap in the number of microplastics; this could be attributed to planting activities (ploughing and fertilization), irrigation, differences in soil texture, and climatic conditions (amount of rainfall) as well as the openness of the surface water, which makes it prone to atmospheric surface runoff and other environmental contaminants. Our results also agree with previous postulations that microplastics can penetrate the soil and contaminate the groundwater and aquifers through infiltration and other contamination sources (MORA et al., 2021; SU et al., 2021; O'CONNOR et al., 2019; PANNO et al., 2019). Additionally, cracks in the soil (as shown in *Figure 2B*) might act as pathways for microplastic contamination of the groundwater. Taken together, these results imply that groundwater is prone to microplastic contamination. Hence, microplastics could potentially be consumed directly in areas where groundwater is used as drinking water without proper treatment.

Table 1 shows that the morphological structure of the microplastics found in the groundwater of the area comprised only fibers and fragments. Of nine microplastic particles found in the area, fibers were most abundant (seven particles), followed by fragments (two particles). These morphological structures were found in two boreholes (1GW and 2GW; *Table 1*). PANNO et al. (2020) and SU et al. (2021) similarly reported fibrous materials as the main contaminant structures in Illinois, USA, and Jiaodong Peninsula, China, respectively.

Table 1
Abundance and morphological structure of MiP in the groundwater

Sample ID	Actual depth (cm)	Perched depth (cm)	GPS Coord.	MiP (No.)		Total (No/l)
				Fiber	Fragment	
1GW	160	100	N 461728.64292, E 201021.2364	3	1	4
2GW	120	100	N 461728. 61988, E 201020. 7858	4	1	5
3GW	120	100	N 461728.5093 E 201019. 8282	0	0	0
Average						3

Conclusion

This case study is among the first group of studies to provide detailed information on macroplastic and microplastic contamination in greenhouse farmlands and microplastic contamination in the related soil profiles and groundwater. For macroplastics, 6.4 kg ha^{-1} were recorded for the entire greenhouse farmland area, and most of the macroplastic contaminants were agro-related plastics, i.e., PE and PVC, typically sized 1–5 cm. Moreover, greenhouse farming released microplastics into agricultural soils, with the highest abundance found in shallow soils (0–20 cm) relative to soils at deeper levels (20–40 cm). The level and distribution of microplastic contamination in the soil profiles were also determined, and microplastic particles were found in the groundwater of greenhouse farmlands (mainly plastic fibers). Hence, groundwater from such areas must be treated before human consumption and used in irrigation to reduce the microplastic load in the human body and agricultural soils, respectively. Additionally, farmers and stakeholders must take greater care to clean and dispose of plastics in greenhouse farming areas. Finally, this research provides insights that could further research microplastic contamination in the soil profile and groundwater.

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