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Quantification of macroplastic litter in fallow greenhouse farmlands: case study in southeastern hungary

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Abstract

Background Plastic greenhouse farming has become widespread worldwide because of its contributions to various agricultural production. However, it also generates plastic waste in large quantities and pollutes farmlands. Contrary to studies on microplastics, few studies have quantified macroplastic contamination in agricultural farmlands despite its contribution to the production of microplastics through fragmentation. Thus, there is a paucity of knowledge on the levels and characteristics of macroplastics in greenhouse environments. Thus, this study aimed to quantify and examine the macroplastic litter on soil surfaces under fallow greenhouse farmlands.

Results The study was conducted at three sites in Southern Hungary, where the usage of plastic greenhouses is very common for cultivating vegetables. On the studied fallow plots, the overall mean abundance of macroplastics was 431 pieces/ha or 6 kg/ha. Most of the fragments had 0.5- to 5-cm sizes. The macroplastic fragmentation in the area was well detected and was an ongoing process. The dominant plastic types were polyethylene and polyvinyl chloride in the form of films and fragments. The results showed that agricultural litter comprised 90% of the total contamination, whereas nonagricultural litter (10%) due to illegal littering also appeared on the plots.

Conclusions Given that macroplastics were found in the studied greenhouse farmlands, we recommend the following: (1) careful cleaning and disposal of plastics on greenhouse farmlands and (2) prevention of greenhouse farmland contamination by external and nonagricultural contaminants. Besides, further research is needed to elucidate the duration of macroplastic fragmentation to microplastic contaminants in greenhouse environments.

Keywords Greenhouse farming, Macroplastic, Microplastic, Polyethylene, Agricultural soil, Hungary

Background

Plastic greenhouse farming began in 1953–1954 at the Kentucky Agricultural Experiment Station in the United States. Within a decade, it became widespread worldwide [1]. Globally, plastic greenhouse farming covers 220,000 ha of land and consumes 250,000–350,000 tons of plastic film annually [2]. It is vital for better space management and growing crops in extreme climate conditions, such as in areas with low temperatures, high rainfall, or frequent dry periods [3]. Moreover, it contributes heavily to the production of various agricultural products. For example, the Almeria region of Spain is often called the "plastic sea" comprising an area of more than 35,000 ha, and 3.8 million tons of horticultural products were produced therein in 2016–2017 [4]. Similarly, greenhouse farming in Saudi Arabia covers 5150 ha and produces 487,000 tons of vegetables annually [5].

Polymers have become essential products in greenhouse industries in the form of film sheets, water pipes, strings, and other materials. The most common plastics

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used for greenhouse cover film applications are low-density polyethylene (PE) and ethylene–vinyl acetate copolymers [6]. These polymers are available in different shed nets (e.g., 15%, 35%, 40%, 50%, and 90%) and different colors (e.g., green, white, and transparent) [3]. Other commonly used polymers include polyvinylchloride (PVC), polypropylene (PP), and linear low-density PE.

Plastics in greenhouses have a short lifespan. Decades ago, plastic films were manufactured to last 1–2 years [7]. In recent years, with the inclusion of additives, such as ultraviolet stabilizers and hindered amine light stabilizers (e.g., Ni quenchers, UVASIL 816, and UVASIL 229), the durability and performance of these plastic films have improved [8, 9]. Indeed, the weathering and early aging of plastic films have been reduced substantially; hence, the lifespan of such films has increased to up to 3 years [2, 8, 9]. Precisely, the addition of stabilizers into plastic films prevents degradation for 2 years of outdoor weathering [10].

Weather variables, such as high temperatures, solar radiation, precipitation, and wind, were found to be among the factors responsible for the physical weathering, aging, and quality deterioration of plastic films [2, 5, 9, 11]. The weather effects on plastic films are gradual but certainly cause stress. Specifically, greenhouse metallic pillars seem to be among the weak points in this regard and may be able to catalyze the photooxidation reactions of plastic greenhouse films [2, 8].

Similarly, the application of agrochemicals containing sulfur, halogens, iron, and chlorine has been confirmed to cause the early aging of plastic films [10]. For example, researchers have shown that sulfur in pesticides is harmful and induces plastic film aging [5]. Meanwhile, Vox et al. [11] compared the quality of sprayed and non-sprayed plastic films and ascertained that the application of agrochemicals increases plastic degradation and aging. Furthermore, environmental pollutants, such as hydrocarbon, nitrogen oxides, sulfur oxides, and particulates, are other external factors that enhance the chemical degradation of polymers by abstracting hydrogen from the polymer chain, which weakens the polymer structure and causes further depolymerization [2].

Extensive greenhouse farming generates plastic waste in large quantities and pollutes municipalities, cities, and farmlands [12, 13]. Abandoned greenhouses appear to contribute more contamination to agricultural areas than those of active greenhouses [14]. In some parts of the world, plastic contaminants are typically disposed of by burning, uncontrolled scattering in fields, or transport to unauthorized dumping sites [2]. In Hungary, used greenhouse sheets could be deposited in waste yards, but these sheets have been recently used for garden equipment within the frame of circular economy programs [15].

Plastic waste is not static. Because of its lightweight nature, it moves horizontally and vertically across and within the soil. Thus, numerous mesoplastics and microplastics have been reported in agricultural soils [13, 16]. Several factors lead to plastic contaminants' vertical and horizontal movement, but the most critical factors include wind, water runoff, and microorganisms [16–20]. Also, smaller macroplastics have been reported in deeper soil layers, and the factors responsible were attributed to soil management practices [16] and cracks on the soil surface [21]. Moreover, the study on macroplastic abundance characterization and fragmentation, especially in plastic greenhouse farmlands, is still limited despite the high coverage of greenhouse farming worldwide.

Most studies on macroplastic contamination and fragmentation were conducted in aquatic environments [20, 22]. Only a few quantified the macroplastics in agricultural setups, such as greenhouse, mulching, and conventional farmlands, even though macroplastics get fragmented and yield microplastics. Most of these studies were conducted in mulch farming systems, whereas only 7% of these were conducted on greenhouse farms [23]. Thus, there is a paucity of knowledge on the level and characteristics of macroplastics in greenhouse environments.

During the weathering of plastics (including greenhouse sheets), various sizes of fragments are produced. The largest ones are macroplastics (≥ 5 cm), which could be weathered to mesoplastics (0.5–5 cm), microplastics (< 0.5 cm), and even smaller nanoparticles (< 1 µm). In this regard, Piehl et al. [24] studied macroplastic contamination in conventional agricultural farmlands in Germany and reported 206 pieces/ha of macroplastics. Meanwhile, Stefano and Pleissner [18] reported much higher contamination in Germany as they found 9247 pieces/ha of macroplastics on arable lands treated with compost. Similarly, large amounts of macroplastics were recovered from the soils of Norway [25]. Macroplastic contamination is a problem in other non-European countries as well. For example, Kundu et al. [17] reported 0.5–5.5 kg of macroplastics on a 50-m by 30-m plot of cultivated land in Tanzania, where the highest weight was found in an area affected by a river. Meanwhile, in mulch farmlands in China, Meng et al. [26] reported 53.7 to 108 kg/ha of macroplastic pollution, whereas Huang et al. [27] described an average of 83.6 kg/ha of macroplastic abundance. Liu et al. [16] reported an abundance of 6.75 ± 1.51 and 3.25 ± 1.04 pieces/kg of mesoplastics in the shallow and deep soil of the suburbs of Shanghai, China. Li et al. [32] reported plastic pollution in mulching farmlands that was ten times higher than that in the control sites of China. According to our preliminary results, the macroplastic concentration on Hungary's greenhouse farmlands' surface was 6.4 kg/ha [13], which is thus considerably less than those in other areas of the world.

These data suggest that the contribution of greenhouse farming to plastic contamination in agricultural farmlands is understudied [12]. Meanwhile, there has been a recent drastic increase in plastic utilization in the agricultural environment compared with those in previous years, which in turn increases the level of plastic contamination. These plastic contaminants end up dumped in ecosystems and cause harm to the environment [10]. Hence, this study aimed to (1) quantify the level of macroplastic contamination in fallow farmlands where plastic greenhouses were used; (2) examine the origin, morphological structures, and polymer composition of macroplastics; and (3) determine the level of macroplastic fragmentation to microplastics. Therefore, this research provides information for stakeholders, policymakers, farmers, and scientists on plastic contamination in agricultural lands. Moreover, it provides first-hand information on the best practices for properly dumping plastic contaminants and how these contaminants could be reused within the frame of circular economy programs. Furthermore, this research supports future monitoring studies on macroplastic and microplastic contamination in the environment.

Materials and methods

Study site

The fruit and vegetable export of Hungary reached 1128 million euros in 2022 [29], and a considerable amount of these fruits and vegetables was produced in greenhouses. Plastic and glass greenhouses covered a total area of 697 ha in 2011 in Hungary [30, 31], which increased to 778 ha by 2021 [32]. The covered area of greenhouses started to grow rapidly after 2012 but remained almost at the same level since 2015 (Fig. 1a). Our study was performed in the Békés and Csongrád Counties (SE Hungary), where the total areas covered by greenhouses (23.9 and 17.2 ha, respectively) were relatively low on a country scale as the climate conditions therein were the most favorable for vegetable farming within entire Hungary. These climate conditions were probably also responsible for the gradual decrease in the areas covered by greenhouses since 2015 in these counties, especially in Csongrád (where the number of sunny hours is the highest) (Fig. 1b).

In southeastern Hungary, plastic and glass greenhouse farming are very popular because of the horticultural traditions of the area and the existence of thermal waters to heat the greenhouses. In this study, three farmlands were selected according to size (0.12–1.52 ha) and the history of the establishment and abandonment of the greenhouses. The farmlands were selected because of their similarities in farming technology (vegetable farming), history (they are now fallows), topography, and climate. This study was conducted next to the city of Szeged (N 46.28990, E 20.18043); going north, a site at Szentes was studied (N 46.5150, E 20.3325), and a third abandoned greenhouse was sampled further NE at Szarvas (N 46.3907, E 20.1526) (Fig. 2). The climate of the sites was warm and dry as the mean annual temperature at the southernmost Szeged was 10.5 °C, which decreased to 10.3 °C toward NE (Szarvas). The annual precipitation was 500–550 mm at all sites. Similarly, the annual sunshine hours were 2020–2040 h/year in Szeged, which slightly decreased toward the north to 2000–2020 h/year for Szentes and Szarvas.

All sites were located on a plain area, but Phaeozem soil developed on loess [33, 34] at two of them (Szeged and Szentes), whereas the natural soil type was Chernozem [33] developed on infusion loess in the third study area (Szarvas).

At Szeged, the greenhouses were built in the 1990s, and tomato was cultivated before they were abandoned in 2015. Meanwhile, the greenhouses at Szentes were

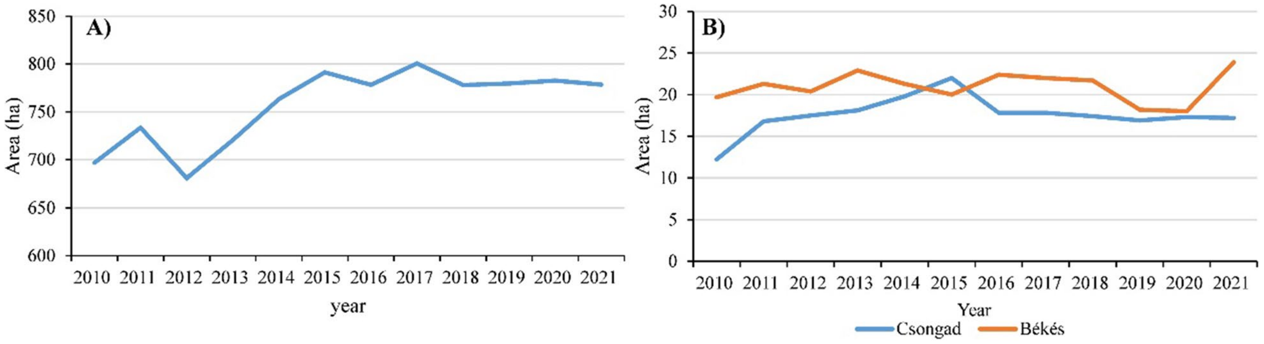


Fig. 1 Total areas covered by glass and plastic greenhouses. **a** Hungary; **b** Csongrád and Békés Counties. (Data source: [32])

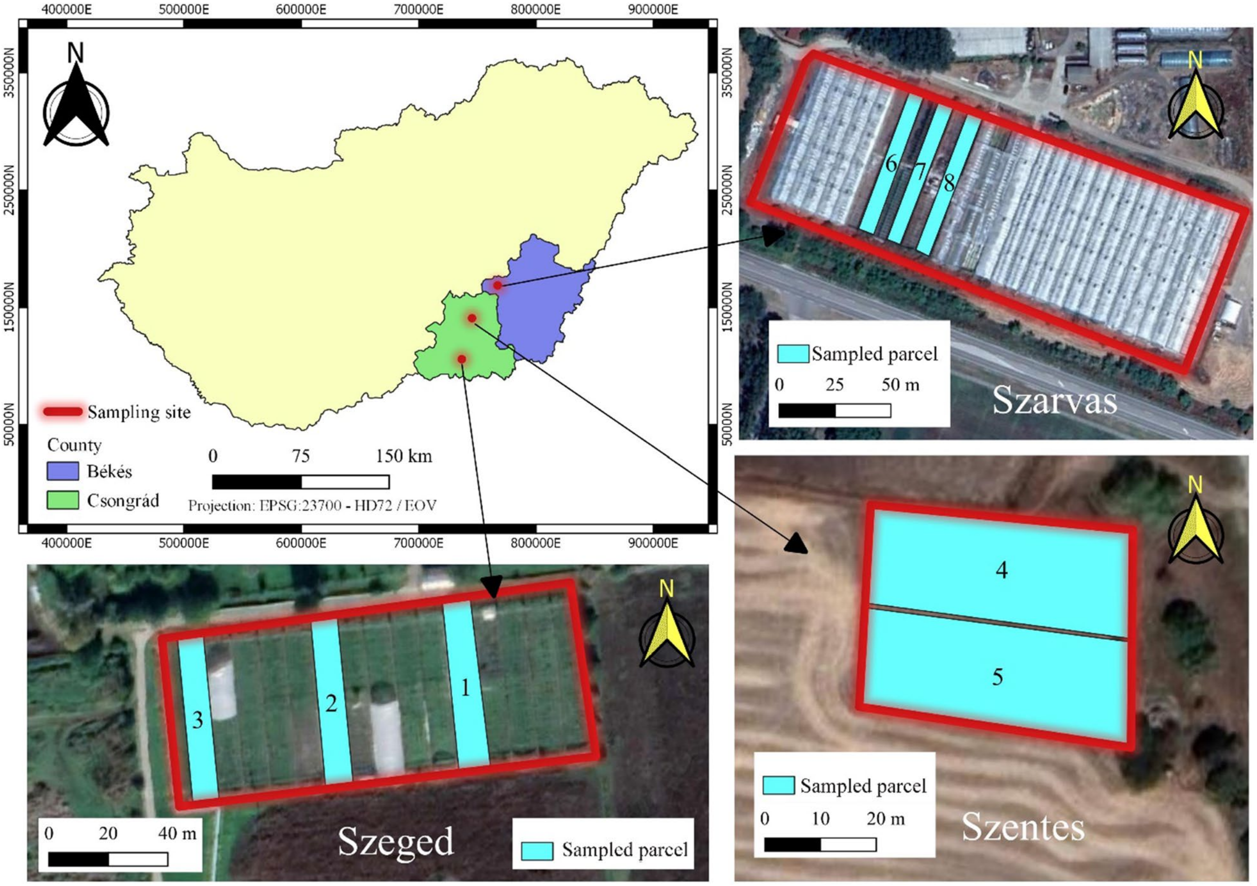


Fig. 2 Abandoned plastic greenhouse parcels in three towns in SE Hungary where the study was performed

established also in the 1990s and were used for pepper seed production before they were abandoned in 2011. Similarly, in Szarvas, the greenhouses were established in the 1990s and have been abandoned since 2017. This site was used to produce tomato, pepper, lettuce, and cucumber. The studied greenhouse farmland areas were probably abandoned because of economic factors.

Sampling and laboratory work

Sampling was performed on rectangular parcels used as greenhouse farmlands. As the structures of the plastic greenhouses were similar, the parcel sizes were also comparable (Szeged: 470 m^2; Szentes: 440 m^2; Szarvas: 500 m^2). Systematic random sampling was used in the greenhouse farms as three parcels were selected at Szeged out of 15 and out of 30 plots in Szarvas. In Szentes, only two parcels were abandoned, and they were not part of a greenhouse field; thus, both were selected because of their similar sizes.

Two observers picked and collected all visible macroplastic debris on the surface of each selected parcel. All collected plastic particles were precleaned to remove the attached soil by scrubbing their surfaces. The materials were later stored in large PE plastic bags, and they were transferred to a laboratory for further analysis.

This study adopted the method developed by Huang et al. [27] with minor modifications. The collected macroplastics were submerged into 15-l buckets filled with tap water and soaked for 48 h to remove all impurities and attached soil particles. The plastics were rinsed thereafter. The water used for cleaning was passed through a 5-mm sieve to catch all macroplastics. The larger and retained plastic materials were combined and dried for 4 days at room temperature. Subsequently, the macroplastics were separated, counted, and measured based on size, shape, color, polymer composition, and possible source types (agricultural and nonagricultural). All morphological categories were counted and weighed using an electric analytical balance. The size of the macroplastics was measured at the contaminants' longest axes for size categorization using a millimeter precision ruler. The macroplastic pieces were grouped into the following size classes: 0.5–1.0, 1–5, 5–10, 10–15, and > 15 cm. These categories were further divided into larger microplastic particles (0.5–1.0 and 1–5 cm) and smaller macroplastic particles (5–10, 10–15, and > 15 cm). The contaminants were also categorized by their color into transparent white, gray, blue, black, red, and green. Similarly, they were also grouped into shapes based on their physical appearance (e.g., film, fragment, and fiber). Approximately 10% of the macroplastic pieces were taken to a Raman spectroscopic analysis for polymer composition identification; thus, they were grouped into PE, PVC, polyethylene terephthalate (PET), and PP. The contaminants were finally categorized according to their probable origin. Agricultural contaminants were those directly related to agriculture and were products of agricultural usage. These included aged plastic greenhouse films, fragments of broken irrigation pipes, stings, agrochemical bottles, and packages. In comparison, nonagricultural plastic contaminants probably had a communal waste origin, and they were not directly related to agriculture. These included candy and biscuit wrappers and disposable cups. Meanwhile, the microplastic contents of the soils on the same parcels were studied by Saadu and Farsang [13]; thus, we could analyze the fragmentation of macroplastics into microplastics by referring to their results. A bare minimum of plastic materials was used during sampling and laboratory analysis to prevent contamination.

Results

Macroplastic abundance

Macroplastic litter was observed in all sampled parcels of the greenhouse farmlands, where the overall mean abundance was 431 pieces/ha. The highest abundance was recorded in Szeged (867 pieces/ha), followed by Szarvas (352 pieces/ha). The lowest abundance (75 pieces/ha) was recorded in Szentes (Fig. 3). The overall mass average of macroplastic pollution was 6 kg/ha. The highest abundance was recorded in Szarvas (10.3 kg/ha), followed by Szeged (6 kg/ha) and Szentes (1.1 kg/ha). Thus, the fallow greenhouse sites at Szeged are significantly more polluted by macroplastic, than the other farmland areas.

Size and fragmentation

The macroplastic sizes were categorized into five fragmentation categories. In Szeged, the most abundant size was 5–1 cm, and the least abundant was the size class of 15–10 cm (Fig. 4). Conversely, in Szentes, only two categories were recorded, and large particles (> 15 cm) were more common than small ones (10–5 cm). In Szarvas, the most abundant size recorded was 1.0–0.5 cm; the other classes had quite similar distributions, though the least abundance was recorded at the class of 5–1 cm.

In terms of weight abundance, the most abundant class was > 15 cm (73%) and the smallest total weight was recorded at 1.0–0.5 cm (0.07%) in Szeged (Fig. 4). In contrast, in Szentes, most of the macroplastics (99%) had a size over 15 cm and only 1% of the measured macroplastics belonged to the 10–5-cm class. In Szarvas, the largest particles (> 15 cm) had the highest abundance (70%), followed by the classes of 5–1, 10–5, and 15–10 cm. The least abundance (0.07%) was recorded in the 1.0–0.5-cm class.

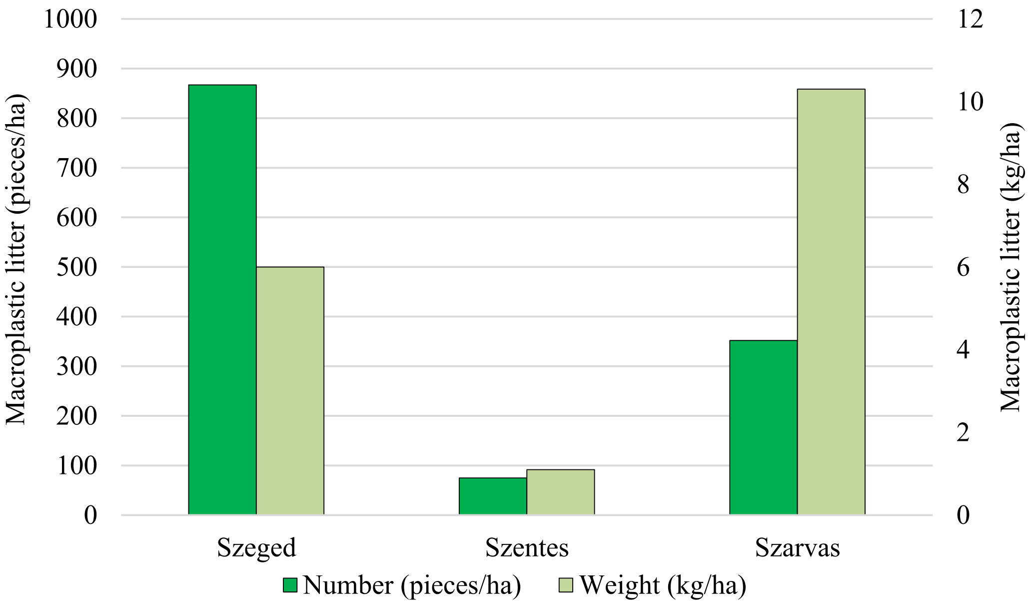
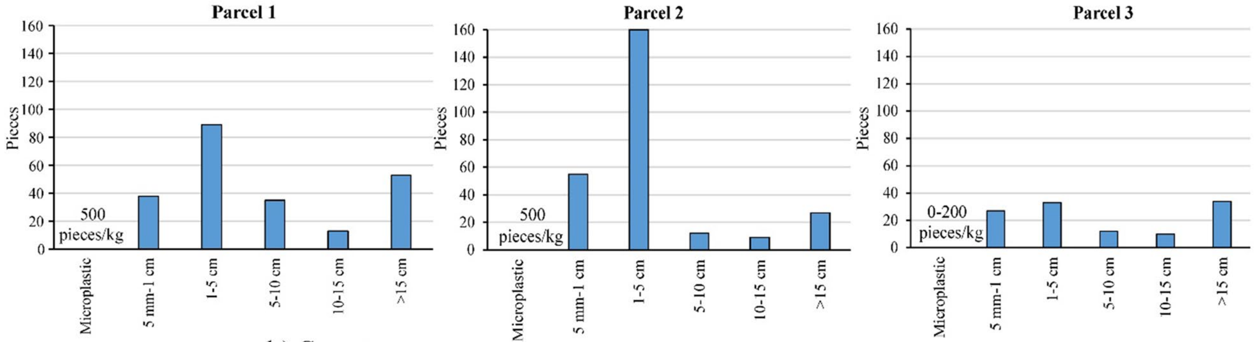
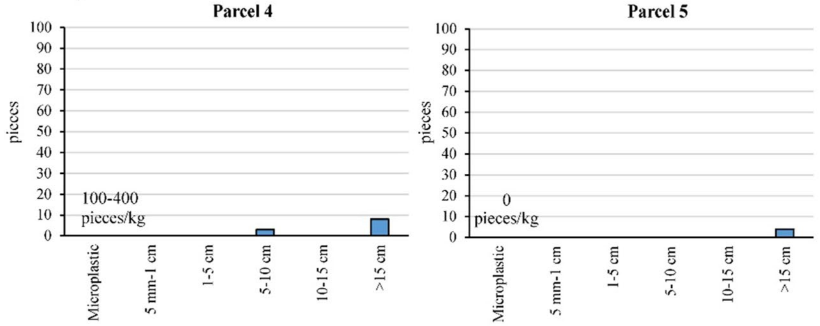


Fig. 3 Mean macroplastic abundance (in number and weight) at the studied parcels

a) Szeged



b) Szentes



c) Szarvas

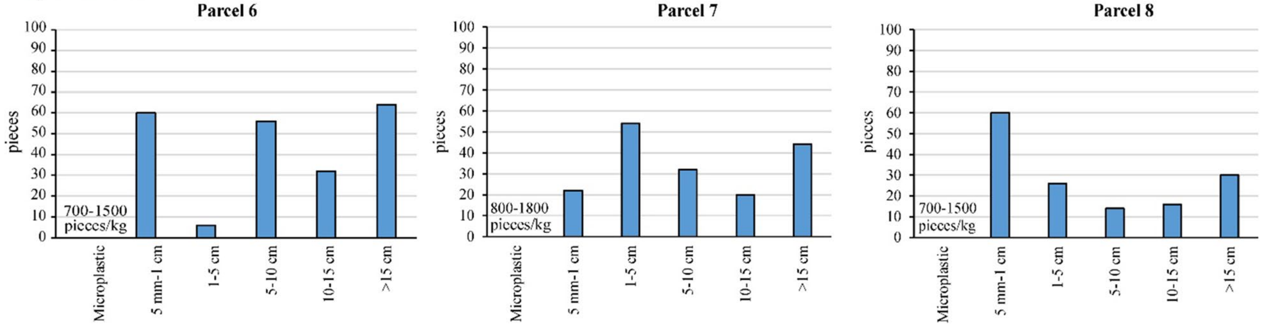


Fig. 4 Macroplastics and microplastics collected from the fallow greenhouse plots at three study areas. (**a**) Szeged. (**b**) Sentes and (**c**) Szarvas

The size classes also referred to the fragmentation process of macroplastics to microplastics (Fig. 4). In Szeged, macroplastic fragmentation was well detectable in all parcels as smaller macroplastic particles (10–0.5 cm) already had a higher number than the number of larger plastic contaminants (>10 cm). Besides, the average number of microplastic found in the soils was 366 pieces/kg [13]. This affirmed that macroplastic fragmentation was an ongoing process and that their breaking up into microplastics had already taken place. The sites at Szarvas were similarly contaminated; fragmentation was also an ongoing process as smaller macroplastic items were almost twice more abundant as the larger macroplastics. Furthermore, an average of 1000 pieces/kg of microplastics were found in the soils of the area [13]. The parcels at Szentes showed minimal fragmentation, probably because only a low number of macroplastic litter was detected on the surface of the greenhouse. Also, the number of microplastic contaminants found in the soils was only 0–400 pieces/kg [13].

Shape and color

In the studied plots, the macroplastics had film, fragment, and fiber shapes (Fig. 5a). Most items were plastic films, accounting for 74–95% of the total contaminants. Another important plastic shapes were fragments, accounting for 15–25% of the contaminants, but they were recorded only in Szeged and Szarvas. The fibers were the least abundant contaminant type. Although it was recorded in all sites, its abundance was minimal as

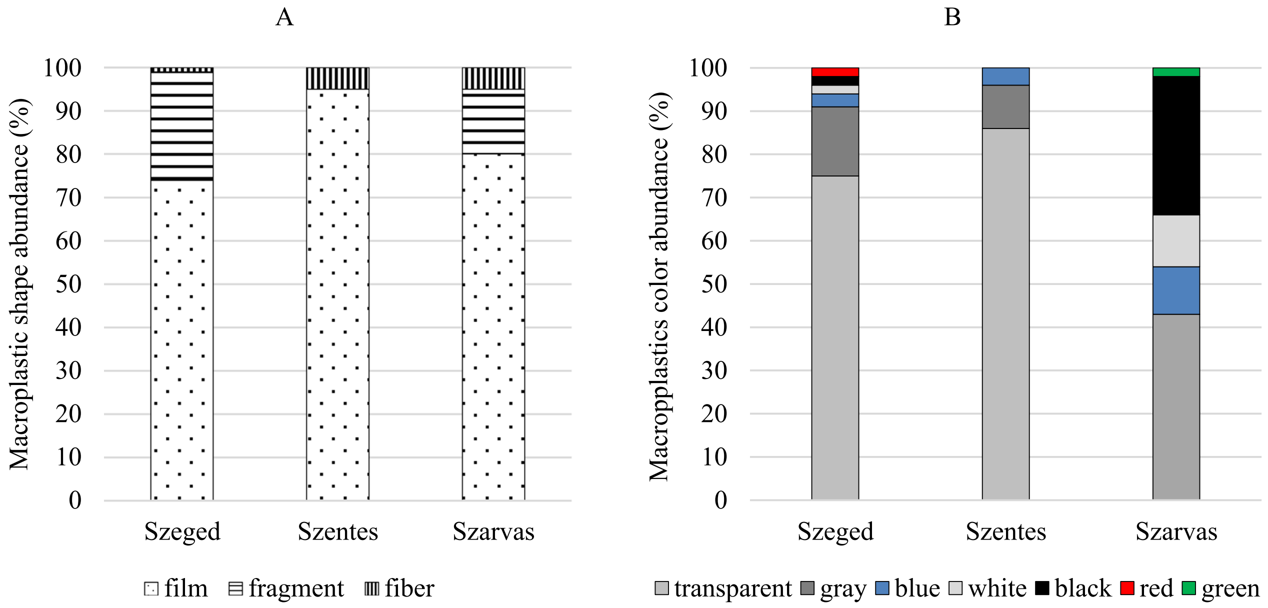


Fig. 5 Morphological (**a**) and color types (**b**) of macroplastics

it accounted for only 1%–15% of the contamination. The highest fiber abundance was recorded in Szentes, followed by that in Szarvas, whereas the least was recorded in Szeged.

A total of seven colors were recorded throughout the areas: transparent, gray, blue, white, black, red, and green (Fig. 5b). The distribution of colors was not uniform; six different colors were recorded in Szeged, only three in Szentes, and five in Szarvas. Transparent macroplastics were the most common (68%), followed by black (11%), gray (9%), white (6%), and blue (6%) ones. The least (< 2%) recorded colors were green and red.

Polymer composition

Four different plastic types were detected on the plots: PE, PVC, PET, and PP (Fig. 6b). As expected, PE was the most abundant plastic contaminant in all sites, accounting for 79–93% of the total abundance (Fig. 6a). Meanwhile, PP was the least abundant (2–4%) contaminant. All four polymers (PE, PVC, PET, and PP) were discovered in Szeged. Considering their weights, the weight of PE was over four times higher than that of PVC, whereas the weight of PVC was six times higher than those of PET and PP altogether. Meanwhile, unlike in Szeged and Szarvas, only two polymers (PE and PP) were found in Szentes, where PE was nine times more abundant than PP. In Szarvas, PE was also the most abundant at over six times the abundance of PVC, whereas the PVC abundance was three times higher than that of PET and two times higher than that of PP.

Types of plastic contaminants

This study showed that not all macroplastics had agricultural origins (Fig. 7). The overall abundance reflected that the agricultural litters comprised only 90% of the total litter; thus, 10% of these litters had nonagricultural origins. The nonagricultural contaminants in Szeged were twelve times more abundant than that in Szentes and twice higher than that in Szarvas.

Discussion

Macroplastic abundance

This study quantified the abundance of macroplastic litter in abandoned greenhouse farmlands. On average, 431 pieces/ha were found in the Hungarian study sites, which equals 6 kg/ha of macroplastic pollution. Despite the limited number of studies on macroplastic contamination in agricultural soils, our result conformed with those few studies that quantified macroplastic contamination on agricultural surfaces. Considering the number of macroplastics in the Hungarian study sites, the macroplastic litter abundance was twice as much as that in the agricultural soils of Germany, as reported by Piehl et al. [24] (206 pieces/ha). Similar contamination was reported in Tanzania, where Kundu et al. [17] reported 3.3–36.6 kg/ha of macroplastics on agricultural soils, but much higher pollution was indicated by Huang et al. [27], who found 83.6 kg/ha of macroplastics in Chinese mulch farmlands. Comparing our results with those of Kawecki and Nowack [35], the Hungarian sites in this study were considerably more polluted, as they reported a median

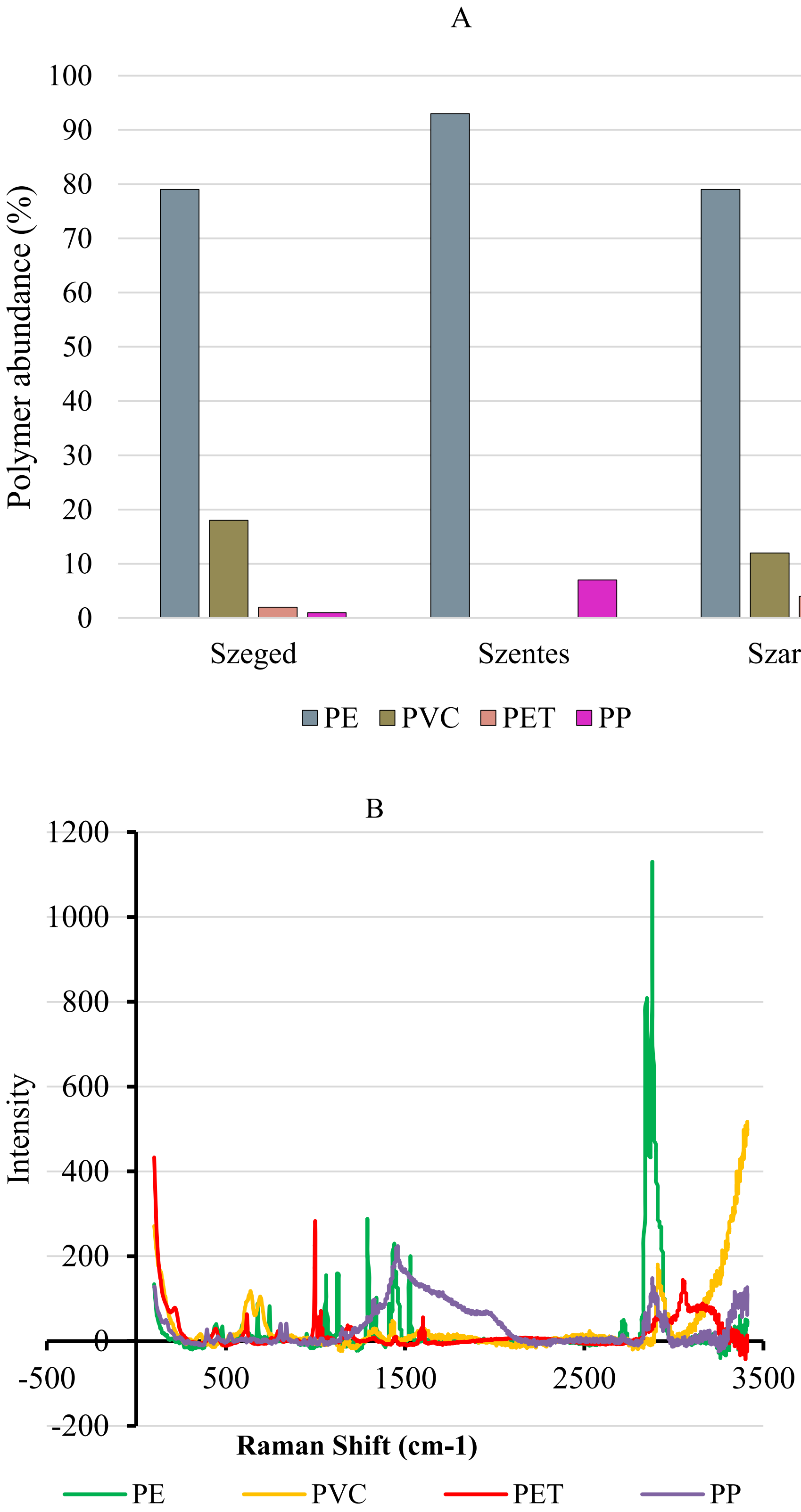


Fig. 6 **a** Polymer compositions of the macroplastics collected on the plots of abandoned greenhouses. **b** Raman spectra of the identified polymer types

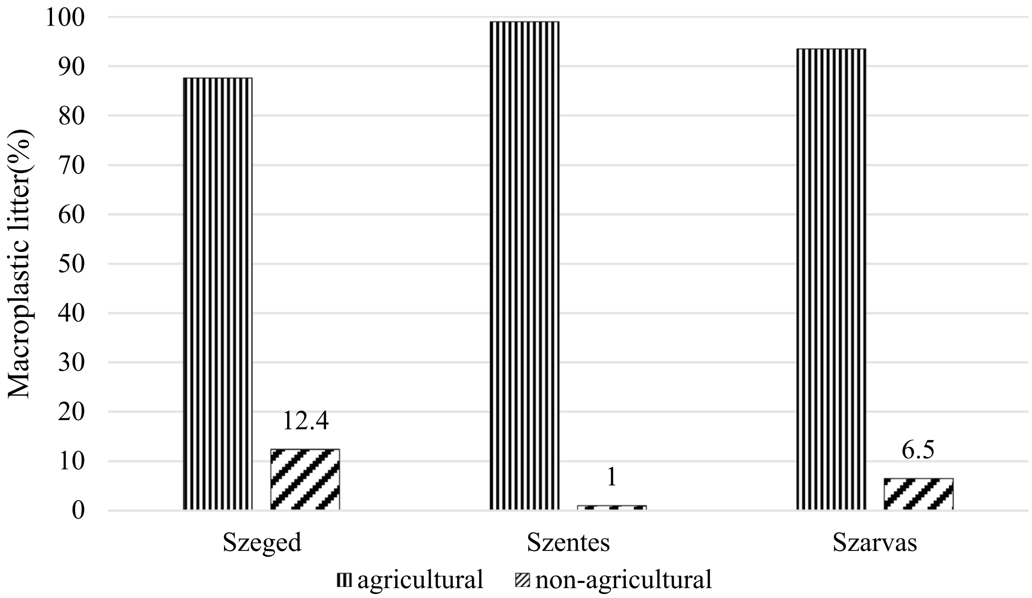


Fig. 7 Abundance of macroplastics with agricultural and nonagricultural origin

emission rate of macroplastics of 0.0006 to 0.06 kg/ha per year in Switzerland. However, our results show much lower contamination than those in the findings of Stefano and Pleissner [18], who reported a macroplastic contamination value of 9247 pieces/ha in arable land treated with compost in Germany. The disparities in the macroplastic abundance in these studies could be explained by the differences in the management of general agricultural areas and greenhouse farmlands.

High variability between macroplastic abundance values was well reflected by the studied sites. The macroplastic contamination recorded in Szeged was ten times higher than that in Szentes and twice higher than that in Szarvas. These differences might be attributed to the higher level of solar radiation (2020–2040 h/year) at Szeged compared with those in other areas as solar radiation increases the aging of greenhouse films [2, 9, 11].

Another possible reason for such a disparity may be the differences in the duration of greenhouse farming, duration of farmland abandonment [16, 26], greenhouse size, clearing activities, and climate. For example, the high abundance of macroplastic contaminants in Szarvas might be attributed to the duration of greenhouse farming because the area underwent greenhouse farming for a long period of 27 years. Meanwhile, the low level of macroplastic contaminants in Szentes might be related to the short duration of greenhouse farming therein (21 years). Besides, the greenhouses at Szentes were not part of a larger greenhouse farm, so cross-contamination from neighboring greenhouses could not increase the macroplastic pollution of the plots. In addition, the area at Szentes has been abandoned since 2011, whereas greenhouse farming was finished 4 and 6 years later in the other two areas. The reasons for the abandonment include climatic conditions as well as economy factors. In this regard, an area with long abandonment history presumably has less macroplastic litter because climatic parameters, such as water and wind, were confirmed to carry light macroplastic contaminants to other areas [17]. This result indicated that the long-term practice of plastic greenhouse farming exposes the land to macroplastic contamination. At the same time, the result indicated that long-time abandonment might lead to the scattering of these contaminants to other areas as well.

Size and fragmentation

This study found different sizes of macroplastics in the studied greenhouse farmlands. This result agrees with other relevant findings, which concluded that plastic materials in mulching farmlands are fragmented into different sizes and categories [16, 26, 27]. Similarly, the fragmentation of plastic contaminants has been reported in conventional farmlands and along riverbanks [17, 24]. The rate of litter fragmentation affects the availability of macroplastics on the surface. For example, the climatic conditions and agrochemical use in Szeged increased the rate of fragmentation and size formation of macroplastic litter by inducing the quality deterioration, stress, and aging of plastic materials, thus resulting in a greater number of contaminants than those in other farmlands (Fig. 3).

Furthermore, our results support the hypothesis that plastic film covers and other plastic materials in greenhouses break down into smaller pieces. The fragmentation process is gradual, and it occurs as a result of the combination of climatic, agrochemical, structural, and environmental factors [2, 9, 11, 36]. The fragmentation of plastic materials requires time, gradually starting from visible cracks to holes on the particle surface and finally fragmenting into smaller pieces [28]. In this study, the degree of fragmentation occurred in the following order: Szarvas greenhouse > Szeged greenhouse > Szentes greenhouse. Similarly, microplastics were found in the soil of the studied plots [25], indicating a gradual, ongoing process. This result conforms to the finding of Li et al. [37], who reported that most of the plastics used in mulch farming break down and form > 2 cm macroplastics. In contrast, the Szentes greenhouse had fewer macroplastic and microplastic contaminants, probably because plastic films and other plastic materials were collected properly after abandoning the plots therein. Another reason might be the horizontal displacement of macroplastic litter from the area other points due to the long abandonment of the greenhouse.

The advanced fragmentation states in our study areas could be increased by high annual temperatures (10.4 °C–10.6 °C), high seasonal temperature variations, high annual solar radiation (2000–2040 h/year), increasing occurrences of heavy rainfalls and hails, and thermal water heating of the greenhouses. In the study areas, PE was the most available plastic material for fragmentation as it was mostly used as cover material for plastic greenhouses. Thus, it received great degrees of environmental stress, such as solar radiation, precipitation, wind, and atmospheric pollutants [6]. Moreover, the agrochemicals used in the greenhouses were deposited on PE's inner surfaces. Consequently, PE easily broke and formed smaller pieces of microplastics as they were characterized by low densities (0.917–0.960 g/cm^3) and melting points (135 °C), low mechanical strength, rigidity, and hardness [6]. Environmental parameters, such as photooxidation and thermal oxidation, and chemical hydrolysis easily weaken the chemical chain structures of PE polymers and cause aging because PE has a simpler chemical structure than those of any polymer.

Shape and color

Our results indicated that the dominant shape of macroplastics was the film shape, but fragments and fibers also occurred (Fig. 5a). The films inevitably originated from the fragmentation of greenhouse cover materials, which conforms to previous findings that reported plastic films as the main microplastic structure in the soil of greenhouses [13]. Similarly, plastic films were the most abundant contaminants in mulching areas [16, 26, 27, 32]. Their high abundance was because of the intensive use of plastic films in greenhouse farming and because plastic covers have low durability and they litter surfaces [13]. Another reason for the high abundance of films is that nonagricultural contaminants, such as food wrappers and other packages, also fragment into plastic films, and they could be easily transported by wind and water from main roads and urbanized areas to greenhouse farmlands. Moreover, our results support our hypothesis that most plastic contaminants in greenhouse farmlands occur because of the fragmentation of aged plastic covers.

Different colors of contaminants were detected in the area, mostly transparent, black, and gray. These colors tally with the colors of the materials used for greenhouse plastic covers and PVC pipes used for irrigation. These results are similar to those of previous studies that reported different contaminant colors in agricultural soils. For example, widespread colored contaminants were reported in Germany and Tanzania's agricultural farmlands [17, 24]. The reason for the dominance of transparent materials (Fig. 5a) might be that maximum light transmission for plant growth is needed in greenhouses [6]. Other reasons for their adoption are their cheapness, durability, and lightweight properties. Also, fragments with other colors were revealed on land [17], reflecting that other greenhouse plastic materials and nonagricultural contaminants in the area were also fragmented and contributed to macroplastic waste generation. Moreover, these color data contribute to a clearer understanding of the relationship between greenhouse covers and contaminants. Although widespread colors were recorded in the area, the color data trace the contaminants' sources and relationship with greenhouse films.

Polymer composition

The largest proportions of macroplastic polymer compositions (number and weight) revealed by Raman spectroscopy were those of PE and PVC (Fig. 6). These results confirm that the polymer composition of the greenhouse contaminants was PE. The reason was that PE was the most commonly used plastic material in greenhouse farming in the form of plastic films because it is lightweight, malleable, and inexpensive. Besides, it can support weed and disease control [6, 38, 39]. This finding conforms with previous studies, which detected PE as the primary contaminant in agricultural and horticultural surfaces [14, 16, 26, 27]. However, these results differ from those of Kundu et al. [17] for the composition of plastic contaminants in the irrigated farmlands and riverbank of Arusha, Tanzania, where PET was the most abundant polymer. One reason for this disparity is that the riverbanks have multiple contaminant inputs, such as garbage, agricultural plastics, industrial waste, pharmaceuticals, and long-distance riverine transport [38]. In comparison, our findings only concerned plastic contaminants from known sources and origins.

Polymer composition affects the abundance of macroplastics and the size of fragmentation. PE is a low-density plastic that is easily aged and fragmented into pieces, which later increases the number of microplastic particles on the surfaces of greenhouse farmlands. Meanwhile, high-density plastics, such as PVC and PET, had low abundance because they are hardly fragmented; thus, they contribute fewer contaminants to greenhouse surfaces.

Types of plastic contaminants

Our data suggest that the macroplastic contaminants in the area had agricultural and nonagricultural origins. Most of the macroplastics were directly linked to materials used in agriculture, such as old films, broken pipes, and aged fibers that got fragmented under the influence of weather, agrochemicals, and other factors [5, 9, 11]. Meanwhile, nonagricultural contaminants occurred in the area because of illegal waste deposition; thus, litter was transported from nearby roads and rural areas by wind or runoff. According to Kundu et al. [17], environmental factors such as water runoff play a vital role in the transportation and distribution of macroplastic contaminants. In our flat study area, wind transport probably was the most important mobilizing factor. The highest volume of nonagricultural contaminants was recorded in Szeged (12.4%), followed by those in Szarvas (6.5%) and Szentes (1%). The proximity of the Szeged and Szarvas greenhouses to main roads increased the high input of communal contaminants into the greenhouse areas as waste along the road is easily transported to neighboring areas by wind and water runoff [18, 40, 41]. Lastly, the low level of communal contaminants in Szentes resulted from its great distance from the town and the long abandonment of its greenhouse farmlands; thus, even workers did not litter in the area recently.

Conclusion

This study analyzed the abundance, characteristics, and fragmentation levels of macroplastics in abandoned greenhouse farmlands. We found that these abandoned greenhouse farmlands contained macroplastic contaminants of different shapes, sizes, and colors. Consequently, greenhouse farming systems could be considered as one of the main sources of macroplastic litter in agricultural farmlands. The contaminants of agricultural origin dominated the type of contamination, whereas the nonagricultural contaminants contributed to some levels of contamination. PE and PVC in the form of films and fragments were the dominant polymer types as they are commonly used in agricultural practice. Importantly, our results showed that greenhouse macroplastic litter could be categorized into different sizes as larger contaminants break down to form smaller pieces of plastics.

Our results clearly showed that greenhouse farming generates large quantities of plastic litter that pollutes the environment and gets fragmented into microplastic particles that end up in the soil ecosystem. Therefore, unused agricultural equipment in greenhouses must be carefully cleaned and properly dumped to avoid macroplastic and microplastic contamination. Also, policymakers should enact policies for regulating the abundance of used plastics in greenhouse fallows, and guidelines should be offered for farmers on the proper collection of used materials. Finally, official waste disposal sites should be created where farmers could dispose of these used materials for free. Besides, further research is needed to elucidate the duration of macroplastic fragmentation to microplastic contaminants.

Abbreviations

PET	Polyethylene terephthalate
PVC	Polyvinyl chloride
LLDPE	Linear low-density polyethylene
HDPE	High-density polyethylene
PET	Polyethylene terephthalate
PP	Polypropylene

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Author contributions

SI: Conceptualization; Investigation; Data curation; Methodology; Writing-original draft. AF: Resources; Project administration. TK: Supervision; Writing-original draft & Editing.

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Availability of data and materials

All data generated or analyzed during this study are included in this published article.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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