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RESEARCH ARTICLE

Plastics derived from disposable greenhouse plastic films and irrigation pipes in agricultural soils: a case study from Turkey

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Abstract

Plastics are ubiquitous. It has been used in human activities, from agriculture to packaging, infrastructure, and health. The wide range of usage makes plastics an omnipresent pollutant in the environment. This study investigated the abundance and type of plastics in agricultural soil in the Adana/Karataş region in Turkey, where disposable low-tunnel greenhouse plastic films and irrigation pipes were in use. For this purpose, 1 kg of soil samples from the top 5 cm (from the surface) was taken from 10 different sampling locations. An average of 16.5 ± 2.4 pcs/kg was found in the soil samples. The highest amount of plastics was seen at the Bahçe-4 location with 39.7 ± 12 pcs/kg and the lowest amount of plastics at the Karataş-1 location with 0.7 ± 0.3 pcs/kg. The average size of plastics was found to be 18.2 ± 1.3 mm. The average size of plastics originating from greenhouse cover was 18.9 ± 1.4 mm, and from disposable irrigation pipes was 12.5 ± 3.5 mm. It was determined that 41.9% of extracted plastics were microplastics, 36.3% were mesoplastics, 16.3% were macroplastics, and 5.6% were megaplastics. Results indicated that residual plastics decreased in the soil where used plastics were removed after usage. As a result, it is worth noting that a significant amount of plastics remain in soil due to plastics being used in agricultural areas.

Keywords Plasticulture · Soil pollution · Drip irrigation · Low-tunnel greenhouse · Terrestrial plastics

Introduction

The production of plastic reached 368 million tons in 2019 due to its widespread use (PlasticEurope 2020). In Europe, an average of 60 million tons of plastic is produced every year, and 27 million tons of this is stored as waste in landfills (WWF 2018). As of the end of 2021, the total plastic production in Turkey was approximately 10.8 million tons, of which 8.4 million tons were consumed domestically (PAGEV 2021). Excessive consumption of plastic also causes a significant amount of plastic waste. It is estimated that approximately 32 million tons of municipal waste were produced in Turkey in 2018, of which approximately 10% was plastic (Gündoğdu and Walker 2021).

Plastic waste in the environment may undergo degradation and decomposition due to physical, chemical, and biological factors. Recent studies have revealed that many plastics, including plastics reported as biodegradable, break down into smaller fragments rather than decompose (Barnes et al. 2009; de Souza Machado et al. 2018). Therefore, plastics larger than 5 mm turn into particles smaller than 5 mm, often called microplastics (MPs), due to the aforementioned factors. MPs can also be released directly into the environment as micro-sized particles designed for various purposes (e.g., resin pellet, microbead). MPs were first reported in the Sargasso sea by (Carpenter et al. 1972). Since this first report, early studies have mainly focused on the marine and freshwater environments. It is now widely known that MPs now can be found in all ecosystems (including, air, water,

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Highlights

- Soil samples were collected at ten agricultural fields.
- The average number of plastics was 16.5 ± 2.4 pcs/kg.
- The mean size of plastics was 18.2 ± 1.3 mm.
- 41.9% of extracted plastics were categorized as microplastics.
- Almost two of three microplastics (87%) were from greenhouse cover.

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and soil), personal care products, table salt, and seafood (Dehghani et al. 2017; Duis and Coors 2016; Gündoğdu 2018; Gündoğdu et al. 2021; Gündoğdu et al. 2020a, 2020b; Gündoğdu and Çevik 2017; Lusher et al. 2018). Although most of the information we have about MP pollution today is from aquatic environments, the number of MP studies focused on terrestrial environments is increasing (Bläsing and Amelung 2018; Büks and Kaupenjohann 2020; Schell et al. 2021). Even with this increase, little is still known about the abundance and impact of MPs in soils, particularly within agricultural settings.

In recent years, the use of plastics in agriculture has increased significantly (Maraveas 2020). Plasticulture practices are varied and for many purposes, including improving crop productivity, animal nutrition, water use, and reducing food losses. For example, mulching films are used in crop production to suppress weed growth, increase soil temperatures, reduce topsoil and nutrient losses, and reduce soil water evaporation after heavy rainfall (Adhikari et al. 2016; Li et al. 2021). These factors increase crop yields, extend the growing season, and reduce the need for irrigation as well as fertilizer and herbicide applications. However, plastic mulch films are also known to be a significant source of plastic contamination. Their widespread and long-term use, coupled with a lack of systematic collection and management, has led to their accumulation in the soil (Ren et al. 2021). Soil pollution caused by plastics is not limited to mulching films. Disposable irrigation pipes, fruit protection films, and empty agrochemical containers that are poorly managed and abandoned on farms also contribute to agricultural plastic pollution. Büks and Kaupenjohann (2020) state that soils, where plastic-containing agricultural applications are made, contain significant MP residues. The low-tunnel greenhouse plastic films are an important source of MP in arable soils (Huang et al. 2020). This thin-film-type plastic (8–50-μm-thick polyethylene) is thought to be unaffected by biodegradation processes and, therefore, limiting entry to the soil (Qi et al. 2020; Steinmetz et al. 2016). Other sources of MPs in agricultural areas can be listed as wastewater treatment sludge, compost, irrigation with wastewater, surface runoff, and atmospheric deposition (Bläsing and Amelung 2018; He et al. 2018). Previous studies have shown that wastewater treatment sludge (Corradini et al. 2019; Nizzetto et al. 2016; Zhang and Liu 2018), external inputs such as organic fertilizers made from biological wastes (Weithmann et al. 2018), and irrigation wastewater use (Zhang and Liu 2018) make significant contributions to MP pollution in agricultural soil. Thus, the agro-soil ecosystem is recognized as a critical accumulation area of MPs (Rodríguez-Seijo and Pereira 2019; Boots et al. 2019; Qi et al. 2020). MPs in soil threaten human and ecosystem health due to their potential to bioaccumulate in the food web. MPs also risk carrying other pollutants such as pesticides that enter the food chain and harm human and environmental health. MP accumulation in agricultural soil affects soil water holding capacity, soil aggregation, performance, and composition of soil microbial community, soil fauna, and flora which can affect agricultural productivity (Büks et al. 2020; de Souza Machado et al. 2018; Fei et al. 2020; Lehmann et al. 2019; Rillig et al. 2019). MPs also affect organisms that live within and are reliant on the soil environment, including earthworms, snails, and soil nematodes (Lei et al. 2018; Song et al. 2019; Wang et al. 2019).

Plastic applications in agricultural activities are escalating in Turkey as well as all over the world. Plastic greenhouses covered 4270 km^2 of agricultural land in Europe in 2010 (Steinmetz et al. 2016) and has achieved an annual growth rate of 5–10% worldwide in recent years (He et al. 2018). Greenhouse cover plastics have been widely used in greenhouses and soil mulching of farmland throughout the world since the 1970s. Plastics in use in agricultural areas or unmanaged plastic waste can be broken down into MPs by physical degradation, chemical aging, and biodegradation in agricultural environments (Ng et al. 2018; Rezaei et al. 2019). Therefore, agroecosystems with the widespread use of plastic can also be considered continuous MP production areas due to the repeated use of plastics used for agricultural purposes every year. The duration of the plastic greenhouses in the fields is positively correlated with the degradation level. The degradation of PE plastic by ultraviolet (UV) exposure, abrasion by soil particles, and wind erosion in field conditions have been expressed in previous studies (Rezaei et al. 2019; Song et al. 2017).

According to PAGEV (2021), 382,000 tons of plastic produced by Turkey as of 2020 is used for agricultural purposes, with the primary application types being greenhouse and disposable drip irrigation piping. Turkey ranks in the top four in the world in greenhouse cultivation, and ranks second in Europe after Spain (Tüzel et al. 2020). Turkey's total greenhouse area has reached 77,209 ha as of 2018. The low plastic tunnel application is 27.36% of the total greenhouse area (Tüzel et al. 2020). It is worth noting that plastic material in greenhouse applications is relatively high, especially for low-tunnel applications. Although there is not enough data, it can be proposed that disposable drip irrigation pipe applications are also increasing in parallel with greenhouse cover applications. This is the first study to quantify MPs and larger plastics derived from greenhouse covers and irrigation piping conducted on agricultural soils in Turkey. This study aimed to investigate the abundance of plastics in agricultural soils, specifically those that originated from greenhouse cover plastics and disposable drip irrigation pipes.

This study investigated the following hypotheses: both greenhouse film (GF) and disposable irrigation pipe (SUP) usage cause plastic pollution in the soils; removal of plastics after use affects both the number and the size of plastics originating from GF and SUP in the soil. The results aim to guide farmers and decision-makers in better managing the plastic pollution in the fields and further understanding the behavior of plastics in GF- and SUP-applied agricultural soils.

Materials and methods

Study area

The sampling area is the agricultural lands in the Adana/Karataş region of the Lower Seyhan Plain (LSP) where the most intensive plastic-use agricultural activities are carried out. LSP, which is an important region of Çukurova Delta, is an area of 210,000 ha, bounded by the Taurus Mountains in the north, the Berdan River in the west, the Mediterranean Sea in the south, and the Ceyhan River in the east. Yeler et al. (2017) reported that the agricultural product pattern in LSP is wheat in winter and watermelon, melon, corn, cotton, vegetable, and soybean farming in summer. They also noted that it has an important place in citrus production throughout Turkey. This study selected ten different sampling locations where no crops have been planted yet (at sampling time) in the Adana/Karataş region; soil samples were taken from these locations in triplicate (Fig. 1; Table 1). These sites represent different land and plastic uses, including those that do not use plastic at all. It was noted during an initial field survey prior to sampling that the use of sewage sludge is not common for these areas. The study area is located far from other human activities, yet has an intensive agricultural focus. In addition, although there is heavy vehicle traffic in the seasons when agricultural products are transferred after harvest, it is relatively distant from other sources of plastic pollution. However, it is also reported that the process wastes, especially recycling plants, are widely dumped illegally along the irrigation canals, which may also affect the study area (Gündoğdu and Walker 2021). This notwithstanding, all these sources were excluded from the scope of the study.

Sample preparation and plastic extraction

Soil sampling was carried out by combining the soils taken with a steel shovel from 10 randomly selected points close to the center of the field. Samples were taken from the topsoil (5-cm depth) and blended together to make them homogenous. Subsequently, 3 (replicates) × 1 kg of soil was taken from this blend and transferred to glass jars. As a result, three 1-kg soil samples were taken from each field in total. As this study targeted specific sources of plastics, i.e., greenhouse covers and irrigation pipes, the need to control for procedural contamination from the laboratory clothing or equipment during sampling and processing was unnecessary as any plastics from other sources were easily visually eliminated and not counted. However, care was taken not to cross-contaminate samples between field sites by

Fig. 1 Location of the study area and soil sampling points in the fields

Table 1 Characteristics of sampling locations

Location	Plastic usage*¥	Last yield	Plasticulture background	Removal
Bahçe-1	GF and SUP	Watermelon	>10 years	Yes only pipes
Bahçe-2	None	Maize/soy	–	–
Bahçe-3	GF and SUP	Watermelon	>10 years	Yes
Bahçe-4	GF and SUP	Watermelon	>5 years	No
Karataş-1	None	Wheat	–	–
Karataş-2	None	Cotton	–	–
Ataköy-1	GF	Maize	5 years ago	Yes only pipes
Ataköy-2	GF and SUP	Tomato/watermelon	>5 years	No
Ataköy-3	GF and SUP	Watermelon/peanut	<5 years	No
Tuzla-1	GF and SUP	Pepper	>5 years	No

**GF* greenhouse coverage film, *SUP* disposable irrigation pipes

¥The plastic types of GF are polyethylene, and SUP are polyethylene and acylonitrile butadiene styrene

washing equipment between sampling sites, ensuring the glass jars were tightly closed, and keeping samples apart in the laboratory.

The plastic extraction protocol was conducted following methods described by Losh (2015), Frias et al. (2018), and Gündoğdu et al. (2022) with some modifications. Samples were brought to the laboratory, weighed and passed through a stainless steel sieve (Kalyen Co. Istanbul/Turkey) with a 5-mm mesh size to separate particles larger than 5 mm in size (the upper limit for MPs). Then, the jars containing the sieved material were placed in an oven set at 40 °C overnight. After the water in the samples had evaporated, they were removed from the oven and weighed again. The samples were then transferred to sterilized glass jars of 5 l, and ultrapure water was added to 1 cm above the soil. The samples were then left overnight until the soil was fully in solution which eliminated the aggregation caused by the soil structure. All equipment was washed between samples to prevent cross-contamination.

After the whole sample had become a solution, 4 M NaI (with a density of approximately 1.6 g/ml) was added to the sample (3–5 cm above), stirred with a glass rod and left overnight to be able to perform the density separation. After the density separation, the floating materials were passed through a 55-micron mesh size sieve. Then, the material remaining on the sieve was placed in a sterile glass jar, and Fenton reagent (organic matter digestion solution) was added to digest all the organic matter (Hurley et al. 2018; Tagg et al. 2017). The mixture was heated on a hot plate set at 40 °C until the organic matter disappeared completely. After all the organic matter was digested, the solution was kept in a closed fume hood for 1 day to cool, then the solutions were passed through a 55-micron sieve again, and the remaining materials were transferred onto a 0.45-micron pore size membrane filter (Millipore S-Pack HAWG047S6) with the help of a glass filtration system connected to a vacuum pump. The filter paper was transferred into a closed glass petri dish and preserved for microscopic analysis. Filter papers were examined under an Olympus SZX 16 microscope with Canon EOS 450D camera at magnifications between 0.7× and 30×. Known samples of plastic from the GF and SUP were recovered as controls for comparison purposes to enable plastics from these sources to be easily identified in the soil samples. Transparent film plastics originating from GF plastics and black and hard plastics originating from SUP were counted, photographed, and recorded. Plastics larger than 5 mm remaining on the sieve were classified according to their source and measured. Measurements of the photographed particles were also carried out using the Feret's diameter as part of the ImageJ v1.50i program. Whether the particles were plastic or not was checked with a hot needle after the necessary measurements were made. Size classification of plastics was further done as described by GESAMP (2019), and specifically, the following three classes were used: (1) microplastics: <5 mm; (2) mesoplastics: 5–25 mm; and (3) macroplastics: 25–100 mm.

Although it was clear that the plastic particles extracted from soil were GF and SUP residues used in the field, the most representative particles with transparent and black color were analyzed via ATR-FTIR to confirm polymer type. Plastics were analyzed using Thermo Scientific Nicolet IS10 FTIR with a Smart Orbit Diamond ATR System. The instrument was operated in single reflection mode, with a resolution of 2 cm and a mid-IR range of 400 and 4000 cm^{-1}, at 16 scans per analysis. The polymer types of the plastics were identified using the FDM polymer spectra library.

Plastic concentrations are given as pieces/kilogram ± standard error. In the statistical analysis, the Kolmogorov-Smirnov test was applied to determine whether the number of plastics data fit a normal distribution, and Levene's homogeneity of variance test was applied to the data, and if necessary, the natural logarithm transformation was used to ensure the data fit the normal distribution. A one-way ANOVA was used to determine whether the number of plastics differed between locations. An independent sample *t*-test was used to determine the difference in the number and size of plastics between greenhouse films and drip irrigation pipes. Statistical analyzes were performed using SPSS v25 (IBM, Chicago, IL. USA), and Tableau v.20 was used to visualize the data.

Results

During the field studies carried out in September 2020, 10 different field sites were visited. Three areas did not have any plastic application, and seven were fields with both greenhouse cover plastic and disposable drip irrigation applications (Table 1). As shown in Table 1, most farmers do not collect the plastics they use, and of those farmers who use plastics, they have utilized them for more than 5 years. Watermelon, tomato, pepper, and peanut farm types were farms that have used plastics for longer than 5 years.

The mean plastic concentrations from GF and SUP were 16.5 ± 2.4 pcs/kg dry soil across all sampling locations. According to the sites, the highest plastics were determined in the Bahçe-4 location with 37.4 ± 12.0 pcs/kg, and the lowest plastics were determined in the Karataş-1 location with 0.7 ± 0.3 pcs/kg. In the Karataş-2 location, however, no plastics originating from GF and SUP were detected (Fig. 2; Fig. 3). The ATR-FTIR results also show that the extracted film-type transparent plastic particles and the reference GF were confirmed as polyethylene. Similarly, the extracted black fragment-type plastic particles and two different reference SUPs were confirmed as polystyrene and acrylonitrile butadiene styrene (Supplementary material Fig. S1).

Since there is no plastic application (the length of time that we know it has not had plastics used) in Karataş-1 and Karataş-2 locations, the absence or small amounts of plastic fragments was expected. Similarly, a very low amount of plastic was found in the Bahçe-2 location (1.0±0.6 pcs/kg), another location with no plastic application. However, it is thought that the detection of plastics in this area, albeit at a low amount, may be related to the application of plastics in neighboring fields or plastics that remained from previous tenancy. Those who use some of the fields are not the actual owners of the fields, but their lands are used by the tenancy. Therefore, it is possible to propose that the type of agriculture in which plastic application is applied causes a significant amount of plastic to be accumulated in the fields. Using a one-way ANOVA test, it was determined that there was a significant difference between the locations in terms of plastic concentrations (Fig. 2; $p<0.05$).

When investigating the sources of plastics, it was determined that 10.3% of plastics were from SUP and 89.7% from GF plastics. The difference between the number of plastics from SUP and GF plastics in all locations was statistically significant ($p<0.05$). Size distributions of plastics were between 0.11 mm and 185.2 mm, with an average of 18.23 ± 1.35 mm, and did not show a statistically significant difference according to their types ($p>0.05$). However, the size distributions according to regions showed a significant difference ($p<0.05$). The mean size of plastics originating from GF was 18.9 ± 1.45 mm, and the mean size of plastics originating from SUP was 12.5 ± 3.52 mm (Fig. 4).

The number of plastics was compared between sites that removed GF and SUP plastic from fields and where they were not. It was determined that the concentration of plastics in each size category is negatively correlated with the removal of plastics in the field (Fig. 5a).

It has been determined that the mean size of both micro and mesoplastics is relatively smaller when there is no removal of used plastics compared to the sites where plastics were removed (Fig. 5b, c). Although the sizes of the MPs in the fields where only the pipes are removed are smaller than those in the case of no removal, there is no significant difference. This reveals that not removing plastics from the field leads to a decrease in MP size. On the contrary, the

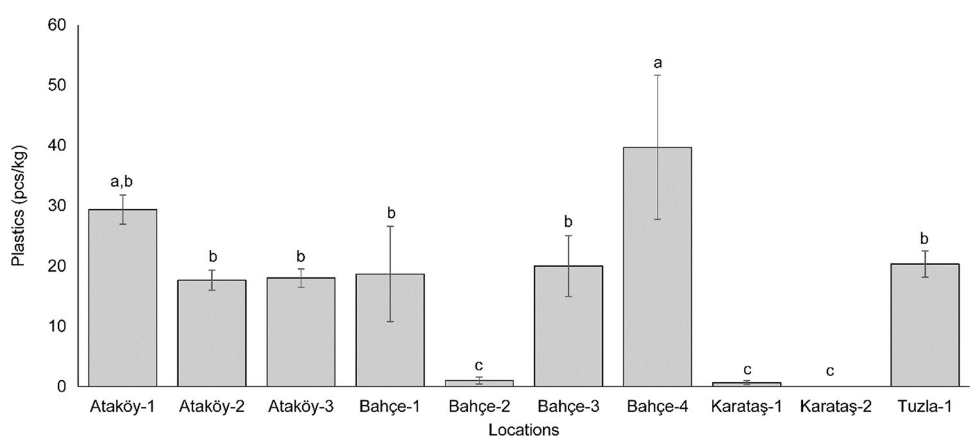

Fig. 2 The number of plastics by location. Bars represent standard errors. The uppercase symbols are based on the DUNCAN multiple comparison tests performed to determine the difference

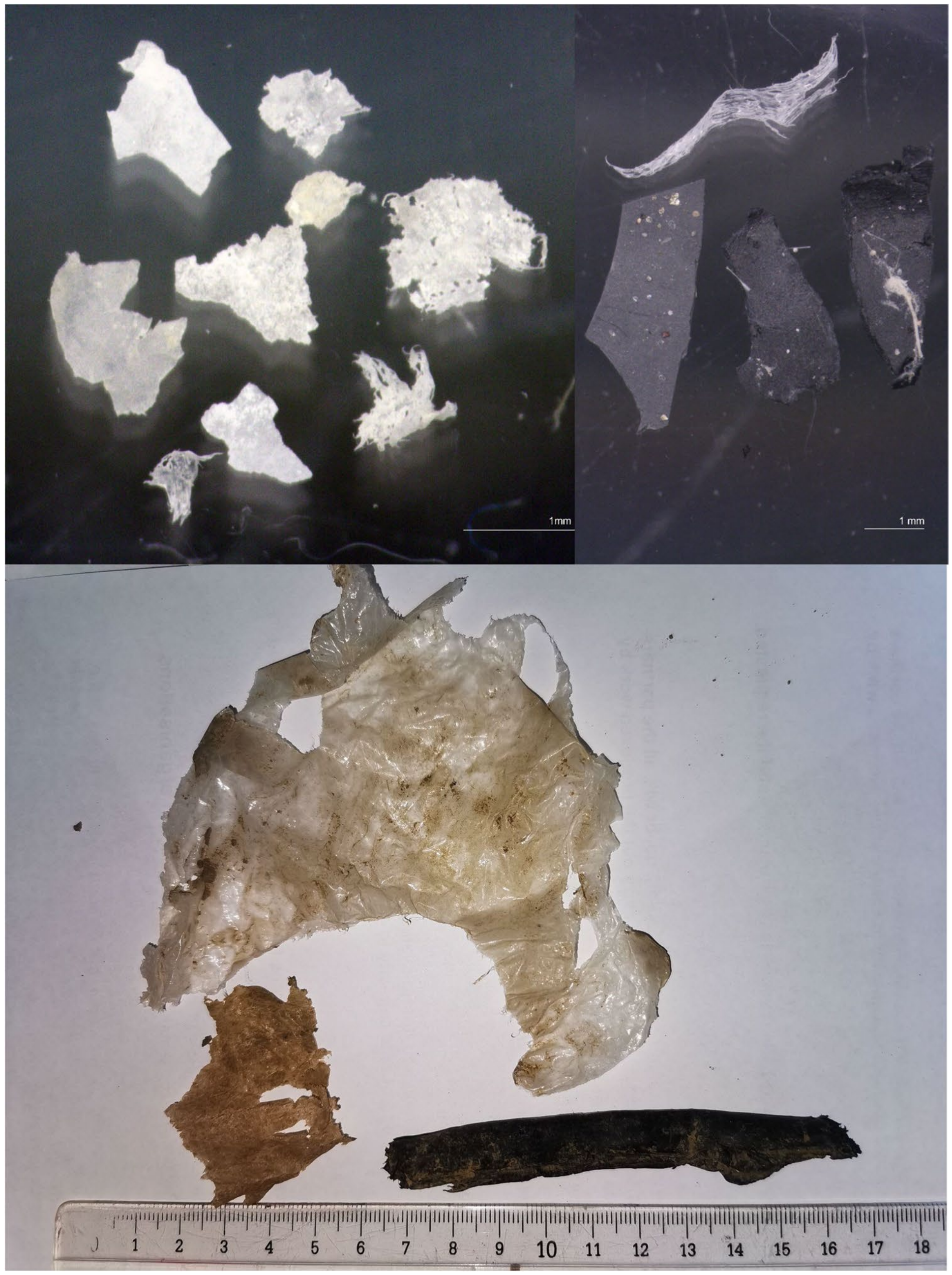

Fig. 3 Upper panels: Microscopic images of microplastics were obtained from sampling locations. Transparent fragments are microplastics from greenhouse cover plastics and dark fragments are from drip irrigation pipes; lower panel: larger residual plastics collected from the field for comparison

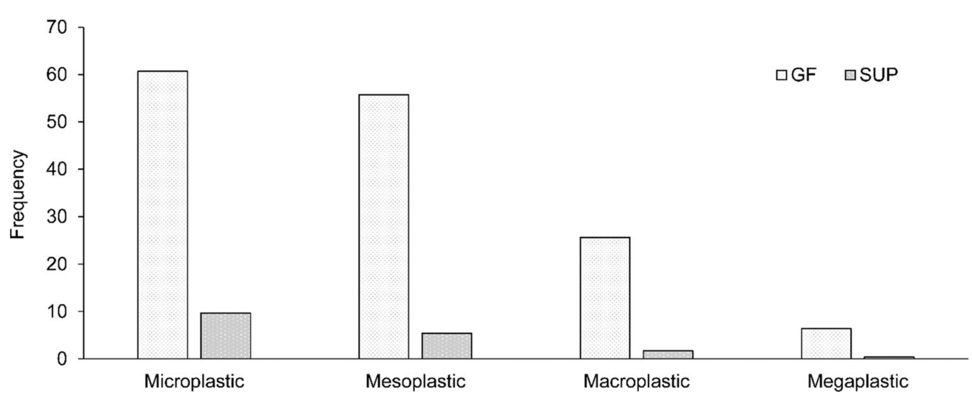

Fig. 4 Size-frequency distributions of plastics by source

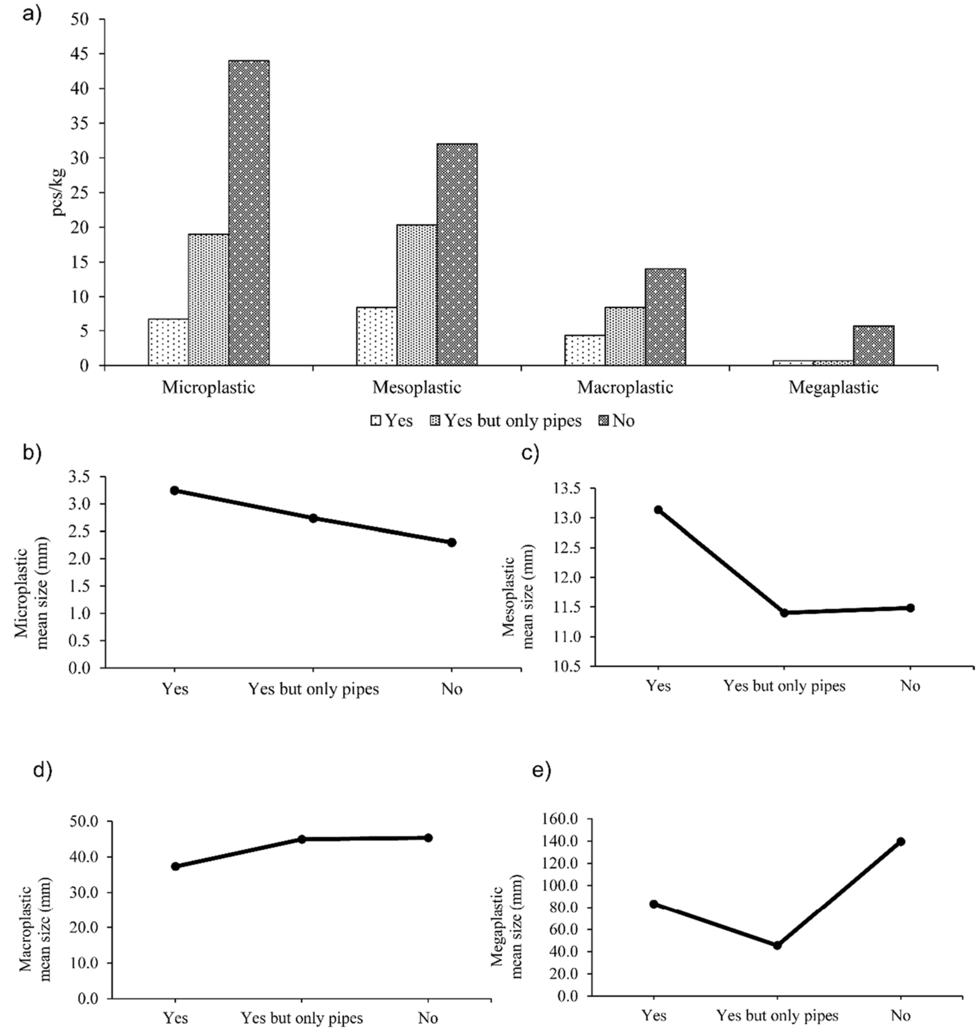

Fig. 5. The effect of the post-use removal of plastics from the soil on the total plastic amount and average height. **a** Change in the number of plastics per size category, **b** change in the mean size of microplastics, **c** change in the mean size of mesoplastics, **d** change in the mean size of macroplastics, **e** change in the mean size of megaplastics

mean size of both macro and megaplastics increases when the landowners do not remove plastics from the field after use (Fig. 5d, e).

Discussion

This study determined the plastic concentrations of arable land in the Adana/Karataş region, where GF and SUP were applied. It has been shown that both applications create plastic pollution in agricultural areas.

So far, only a few studies have investigated plastics in broad categories on agricultural land and our study is the first from Turkey. Plastics were found at nine of the ten study sites, but their abundances varied greatly. The number of plastics found per kilogram of dry soil was 16.5 ± 2.4 pcs/kg.

The number of MPs in total plastics was 11.13 ± 2.31 pcs/kg. This value is considerably lower than the MP amounts of 78 ± 12.9 pcs/kg and 1444 ± 986 pcs/kg, respectively, reported for agricultural soils in China by Liu et al. (2018) and Yu et al. (2021). Similarly, Boughattas et al. (2021) reported a high level of microplastic with 476 pcs/kg concentrations for horticultural soils in Tunisia. However, MPs were reported in this study at a much higher level than the average amount reported by Harms et al. (2021) for northern Germany. This difference could be related to the duration of plastic applications in soils. Li et al. (2022) stated that the abundance of plastics in the fields with shorter durations of plastic mulch film applications was generally lower than that in other areas where plastic mulch film has been used for a comparable amount of time. However, since in this study we could not get reliable information about the duration of the plastic application, we cannot make such statements for this study. Another reason for this difference could be related to the source of MPs that is considered. In this study, only two different potential sources were considered. Therefore, the MP pollution level in this study may be much higher if all MP sources were considered. Further detailed studies need to understand the MP pollution profile, and the relationship between the duration and MP concentration.

The lower abundance of MPs could also be related to the thickness of the applied plastics. Thicker plastics are less likely to disintegrate during removal after harvest (Zhang et al. 2016). Although there is no standard, the thickness range of GFs used in Turkey is 30–800 microns, and the thickness of SUPs varies between 150 and 600 microns. Indeed, in Turkey, GF films are generally thicker than those in Europe and China (25–50 µm vs. 8 µm) (Wang et al. 2022).

The abundance of plastics in GF- and SUP-applied soils was significantly higher than that in no plastic use (Fig. 2). The number of micro-, meso-, macro-, and megaplastics we identified in GF- and SUP-used topsoil was about 47, 78, 17, and 1.2 times higher than that in non-plastic-used farmlands, respectively. This apparent distinction can probably be ascribed to the application of plastic GF and SUP. The amount of plastic not only does differ between plastic-applied soils and non-applied soils but also varies with the removal of plastics after use in plastic-applied soils. The number of plastics we identified in fields where landowners removed plastics (95.67 pcs/kg) has 4.8 times lower plastic concentration (20 pcs/kg) than soils where no removal activities take place. This clearly indicates that removing plastics from fields after use (not or adequately) has significant effects on decreasing the number of plastic concentrations in soil. The collection of plastics after use also has a significant effect on the size of plastics in the soil; with the dimensions of plastics, especially MPs, being relatively larger in soils where plastics are removed. The plastic residues in agricultural soils may present the most significant concerns relating to the impact of plastics on soil quality, ecosystem functionality, and human health and well-being (Zhou et al. 2020; Choi et al. 2021).

It was observed in this study that SUP and GF plastics were randomly found around the fields, all of which are potential sources of plastic contamination if not collected. High amounts of plastics resulting from the widespread use of plastic film also bring some pollution hazards (Jambeck et al. 2015). MPs from GF plastics may reduce soil porosity and air circulation, alter microbial communities, and lead to low soil fertility, with consequent effects on crop seed germination and seedling growth (Kasirajan and Ngouajio 2012). In the personal communication with the farmers during the sampling, the farmers stated that the plastic remaining in the field poses a threat to peanut planting, especially after watermelon planting, as the peanuts cannot grow as they get caught in the plastic residues. Cuello et al. (2015) found that GF plastics significantly reduce soil organic matter content and increase greenhouse gas emissions. Also, several studies show that crop yields decrease when GF residues are found in the soil at rates of up to 58.5 kg/ha (Li et al. 2014; Selonen et al. 2019). GF-derived plastics can adsorb pesticides and other toxins, reduce soil microbial biomass, and transfer potentially carcinogenic and mutagenic phthalate acid esters to the soil (Moreno and Moreno 2008; Fu and Du 2011; Ramos et al. 2015; Wang et al. 2015; Rodriguez-Seijo et al. 2017; Rodríguez-Seijo et al. 2019).

The abundance of plastics in soils varied with land-use types. According to Choi et al. (2021), the second highest abundance of MPs was found in agricultural soil. Moreover, the abundance of MPs in agricultural soils also varied with crop types and the presence of other potential plastic source applications (e.g., composting and usage of sewage sludge). Among those sources, GF and SUP plastics are one of the most significant contributors to plastic residues in soil. After being exposed to UV light, combined with mechanical forces, they broke down into smaller plastics and entered soils, especially in areas with a low removal rate of GF and SUP (Steinmetz et al. 2016; Tian et al. 2022).

Conclusion

Plastic usage in the agricultural sector may have worthy benefits in the short term, but the long-term effects cannot be ignored. In particular, GF and SUP plastics break down into smaller plastics, contaminating the soil, as shown in this study. Over time, plastic breaks down into micro- and even nanoplastics, both of which can enter the food chain. It has been shown that removing plastics from the soil after use significantly reduces the number of plastics in the soil. However, removing plastics does not entirely mean plastic-free soil. Hence, non-petroleum alternatives to conventional agricultural plastics are needed to tackle the physical and chemical effects of plastics in agricultural soil in the long term. This indicates that besides effective plastic collection activities, finding agricultural plastic alternatives is also required. Therefore, decision-makers need to take adequate measures to reduce the plastic pollution load in the soil by coordinating with all stakeholders. In this context, the use of plastic in agricultural production should be controlled with strict protocols, and management plans should be developed. Moreover, future interdisciplinary research is needed to understand the sources, fate, and effects of plastics in agricultural soil.

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Author contribution Rezan Gündoğdu: conceptualization; data curation; formal analysis; ınvestigation; methodology; project administration; resources; software; validation; visualization; writing—original draft; writing—review and editing; Derya Önder: conceptualization; data curation; investigation; project administration, writing—review and editing; Sedat Gündoğdu: data curation; formal analysis; ınvestigation; methodology; software; validation; visualization; writing—original draft; writing—review and editing; Claire Gwinnett: methodology; writing—original draft; writing—review and editing.

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Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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