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REVIEW

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Plastic contamination in agricultural soils: a review

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Abstract

Researchers are focused on the global issue of plastic contamination in agricultural soils because of the known effects of plastics on the soil ecosystem. Previous reviews did not pay attention to plastic sources, standardized extraction methods, soil characterization, and the abundance of plastics in agricultural soils. This study aims to review up-to-the-minute knowledge about plastic contamination studies, suggest the best method for microplastic studies, and propose future research areas. The research about plastic contamination in agricultural soils published from January 2018 to March 2022 was reviewed for this review article. Studies focusing on microplastics in soils other than agricultural soils were not considered in the present review. The data were acquired from several databases, namely Web of Science and Google Scholar. The keywords used to search these databases were "microplastics AND agricultural soils" and "macroplastics AND agricultural soils". Other literature sources were obtained from the reference lists of downloaded articles, and other pieces of literature that directly dealt with macroplastic and microplastic contamination in agricultural soils were obtained from relevant journals and books. Overall, 120 sources of literature, including 102 original research articles, 13 review articles, and five books, were selected, reviewed, and synthesized. As expected, agricultural soils, including arable lands, paddy lands, uplands, irrigation, and greenhouse soils, receive plastic contaminants. The contaminants of different sizes and forms are distributed spatially and temporally in the surface, subsurface, and profiles of the agricultural soils. Unlike previous studies that reported many studies on sewage sludge, the significant sources of plastic contamination in the agricultural soils included mulching, sludge and compost placement, and greenhouses abandonment. The distribution of plastic contamination studies in the agricultural lands is Asia: 60%; Europe: 29%; Africa: 4%; North America: 4%; Latin America: 3%; and Australia: 0%. After careful analysis of the methods used for the plastics contamination studies, the study concluded that floatations with low-density solutions such as distilled water and NaCl are efficient in separating light-density microplastics. In contrast, ZnCl and NaI are incredibly efficient in separating the heavy-density microplastics. Moreover, this review provides insight for future research in the field.

Keywords Greenhouse farming, Microplastic, Macroplastic, Soil, Pollution

Introduction

Global plastic production has increased rapidly since the end of World War II [1], increasing from 1.5 million tons in 1950 to 367 million tons in 2020 [2]. The agricultural and horticultural industries have become major consumers of plastics in the form of film sheets, foam, pipes, and other materials, and these plastics are used for fertilizer transportation, weed control, disease, and pest control, storage, and crop conservation as well as in buildings and structures [3]. Indeed, the application of plastic materials

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in the agricultural sector is required from the nursery stage to the postharvest stage, thus, agricultural and agriculture-related sectors worldwide consume 2,250,000 tons of plastics per year [3].

The particle size of plastic contaminants can be macroplastics (≥ 5 mm in diameter), mesoplastics (5 mm–2 cm) microplastics (< 5 mm in diameter), and nanoparticles (< 1 µm) [4, 5]. Plastic contaminants can also take many forms, e.g., films, fibers, fragments, beads, and foam. In agricultural soils, the primary sources of such contaminants include sewage sludge, coated fertilizers, irrigation water, agrochemicals, etc., whereas secondary sources include the gradual breakdown of larger plastic materials, such as mulching and greenhouse films. Macroplastic and microplastic contaminants are transferred horizontally and vertically across and within soil profiles. The action of wind and water facilitates the horizontal transfer via anthropogenic activities, whereas vertical transfer occurs through leaching, the activities of soil and microbial organisms, and agricultural practices, such as mulching, irrigation, and greenhouse farming [6–8].

The extensive use of plastics in agriculture leads to large amounts of waste generation. Low-density polyethylene (LDPE) is the plastic used most in agriculture, e.g., in greenhouse farming and mulching [9, 10, 11]. The other types of plastics used in agriculture include polyvinyl chloride (PVC), ethylene vinyl acetate (EVA), and linear LDPE (LLDPE) [12–14].

Greenhouse plastic films have a short lifespan. Decades ago, these plastics lasted 1–2 years [13]. In recent years, with the inclusion of additives such as ultraviolent stabilizers and hindered amine light stabilizers (e.g., Ni quenchers, UVASIL 816, and UVASIL 229), the performance and durability of films have improved. 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 [10, 11, 15]. Climatic variables such as high temperature, solar radiation, precipitation, and wind were found to be among the factors responsible for the physical weathering, aging, and quality deterioration of plastic films [9, 14, 15]. Similarly, the application of agrochemicals that contain a chemical compound of sulfur, halogen, iron, and chlorine has been confirmed to cause early aging of plastic films. For example, researchers have shown that sulfur in pesticides is harmful and induces plastic film aging. The sprayed and non-sprayed plastic films were compared; the former showed increased degradation and aging [14, 15]. Lastly, environmental pollutants such as hydrocarbon, nitrogen oxides, sulfur oxides, and particulate enhance the degradation of polymers by abstracting hydrogen from polymer chain which weakens the polymer structure, and further depolymerization [15].

Studies have shown that high concentrations of microplastic contaminants in the soil ecosystem affect soil quality and fertility by altering its structure, bulk density, and water-holding capacity [16–18]. Furthermore, the quality of agricultural products and the growth and photosynthesis of plants are altered by the presence of microplastics [19–22]. In addition, microplastics can adsorb and transport contaminants, such as heavy metals and other pollutants, in the soil environment [23, 24]. Moreover, the health of soil organisms and the enzymatic activities of these organisms are disturbed by microplastic contamination [25]. Moreover, the direct ingestion of microplastics or their consumption through contaminated food, such as fish and agricultural products, is a threat to human health [26]. The presence of microplastic contamination has also been confirmed in groundwater [27–29].

Previous review studies have presented the status of plastic contamination in general soils without considering the contamination of agricultural soil [30–32]. Although other reviews have considered agricultural soils, e.g., He and Luo [31], plastic separation techniques and the distribution of plastic contamination studies have not been explored fully. The present review is novel because it includes the latest information on plastic sampling and laboratory extraction processes, it also reveals the changes that occur in the field over the specified time period, for example in the review of [33], it was revealed that most of the studies focused on the sewage sludge application as source of microplastics to agricultural soils, but this research found that the recent studies diverted to mulching as the main source of microplastics in the agricultural soils. Similarly, the review did not capture the studies of microplastics in the African countries and some part of European countries such as Hungary and Austria. Furthermore, this review reveals the recent distribution of microplastic studies worldwide and the contributions of different plastic sources, such as mulching, sewage sludge, greenhouse farming, and organic fertilization, to agricultural soil pollution. Overall, the aim of this review was to present the current knowledge on plastic contamination in agricultural land and suggest the direction of future plastic contamination studies.

To this end, this review focused on the recent studies of macroplastic and microplastic contamination in agricultural soils; thus, articles published from January 2018 to March 2022 were acquired from several databases, namely Web of Science and Google Scholar. The keywords used to search these databases were "microplastics AND agricultural soils" and "macroplastics AND agricultural soils". Other sources of literature and a few older studies, mainly about plastic types, plastic degradation, sampling, and spectroscopic analysis, were obtained from the reference lists of the downloaded articles, and other sources of literature that directly dealt with macroplastic and microplastic contamination in the agricultural soils were obtained from relevant journals and books were consulted. Studies that focused on microplastics in soils other than agricultural soils were not considered in the present review. Overall, 90 sources of literature, including 75 original research articles, 10 review articles, and 5 books were selected, reviewed, and synthesized.

Distribution of studies on plastic contamination in agricultural land worldwide

The contamination of agricultural soils is ubiquitous, but varies spatially and temporally [34], thus, plastic pollution in agricultural soils is receiving increasing levels of attention from scientists and stakeholders worldwide. Studies on plastic pollution in agricultural soils are being conducted with increasing frequency owing to the known effects of microplastics on the soil ecosystem and agricultural output. The distribution of microplastic contamination studies across various continents is shown in Fig. 1. From 2018, 60% of microplastic contamination studies have been conducted in Asia, in which most studies were conducted in China (37) followed by Japan (3). Europe accounted for 29% of the microplastic contamination studies conducted from 2018, with most studies conducted in Germany (8) and Spain (5). Additionally, Africa accounted for 4% of these studies, with one study performed in each of Tunisia, Tanzania, and Mauritius; North America accounted for 4% of the studies, with studies performed in Canada, the USA, and Mexico; and Latin America accounted for only 3% of the studies, with studies conducted in Argentina and Chile. Lastly, no study was found in Australia.

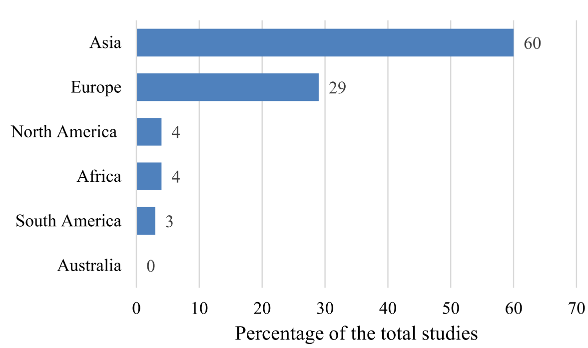

Fig. 1 Worldwide distribution of plastics studies conducted on agricultural land ($n = 120$)

Plastic and plastic polymer types

Various plastic types with different compositions are available, and the plastic material selection depends on the task it will perform. Different plastic polymers with different densities are used for different purposes. For example, different polymer types serve specific purposes throughout the harvest period, e.g., LDPE, LLDPE, and high-density polyethylene (HDPE) are plastic polymers that are commonly used in greenhouse and mulching films. Such polymers are applied in single or multilayer structures depending on the objective, duration of usage, and environmental conditions. Polyethylene plastics are used because of their physical characteristics, ability to maintain a uniform temperature, elongation qualities, protective and disease control capabilities, and utility in water conservation, supply, and storage [3]. PVC is another important plastic polymer type used in the agricultural sector in drip irrigation pipes owing to its characteristics and density. Other plastic polymers used in agriculture include polyethylene terephthalate (PET) in packaging and bottling, polypropylene (PP) in fiber strings, and polyurethane for storage and protection purposes. Polystyrene (PS), polycarbonates, and polymethyl methacrylate are also used in agricultural and horticultural systems. In the previous studies on plastic contamination, LDPE and PP were the common plastic polymers found in agricultural soils [17, 18, 34].

Different agricultural practices lead to the formation of different shapes and compositions of plastic contaminants in the soil. For example, mulching and greenhouse farming techniques produce mainly plastic film-related contaminants at both the macro and micro levels [35, 36]. Microplastic fragments appear in agricultural soils due to the fragmentation of PVC pipes, agrochemical containers, and other microplastic sources. Microplastic microcapsules also appear in the soil following the direct application of plastic-coated fertilizers [37]. Plastic fiber materials occur in the soil owing to their ubiquitous nature in the environment and the frequent application of sewage sludge, compost manure, wastewater, and contaminated irrigation water to farmlands. Plastic microbead contaminants are found in the soil environment because they are present in cosmetic and cleaning products and appear in wastewater. Microplastic foams are also found in agricultural soils due to the application of wastewater and sewage sludge in which they are contained. Such contaminants also arise from using foam materials for storage and fruit protection.

Sources and transportation routes of plastic in agricultural soils

As the use of plastic in the agricultural environment increases, the generation and disposal of plastic waste increases, leading to the increased contamination of agricultural farmland. Plastic contaminants enter the soil from either primary or secondary sources. Primary sources are often unintentionally released into farmland, whereas secondary sources include the disintegration of larger plastic materials due to physical weathering and quality deterioration [38]. Figure 2 reveals the contribution of different plastic sources in the agricultural soils. For example, the figure shows that 16% of the studies were conducted in sludge-amended farmlands. Sewage sludge is applied to agricultural soils for fertilization and is generated from wastewater treatment plants (WWTPs), which systematically separate liquid waste from other contaminants.

However, WWTPs are not 100% efficient in the removal of plastics and other materials; thus, microplastics are often detected in effluents. For example, in the WWTPs of Norway, 500 billion microplastics (mostly plastic beads) are released into the environment via the application of sewage sludge [39]. Gies et al. [40] found that 32.4% of suspected microplastic materials from the WWTPs of Canada enter the soil ecosystem. The concentration of microplastics released into the soil depends on the quantity and duration of sewage sludge application, with higher pollution levels arising from higher application rates. Zhang et al. [41] detected 545.9 microplastic items kg^{-1} after an annual amendment with 30 tons ha^{-1} of sewage sludge in the agricultural soils of Guilin City, China; however, the concentration of microplastics decreased to 87.6 items kg^{-1} when the soil application of sewage sludge was reduced to 15 tons ha^{-1} $year^{-1}$.

Fertilization using controlled-release fertilizers also contaminates agricultural soils with microplastics; it accounts for 3% of plastic sources in agricultural soils, as shown in Fig. 2. To achieve the controlled release of nutrients, such technology is designed to encapsulate the nutrient (e.g., NPK) in a polymer material; however, the encapsulated containers remain in the soil, contaminating the environment because the polymers do not degrade after the release of the nutrient [5]. Katsumi et al. [37] detected a mean microcapsule concentration of 1447 mg kg^{-1} in all paddy fields surveyed. Another important fertilization-related source of microplastics in agricultural soils is manure [42, 43]. Compost manure sources that include the feces of domestic animals, e.g., sheep, poultry, and pigs, are among the primary sources that input hundreds of tons of microplastics into agricultural and horticultural soils annually [22, 44, 45]. The microplastics get to the animal feces due to direct ingestion from the environment and the feed [44].

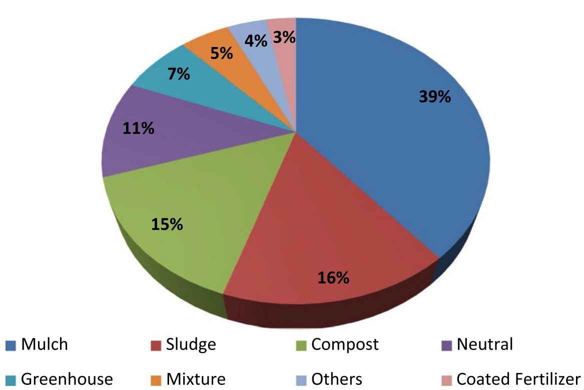

Fig. 2 Sources of microplastics in agricultural soils (*n* = 120)

Plastic contaminants also enter the soil via secondary sources, i.e., as large plastics materials are degraded into smaller particles due to one or more factors, including climate factors, agrochemicals, environmental pollution, and environmental and structural factors [3, 5, 10, 11, 15]. Figure 2 shows that 39% of the studies conducted within this period indicate mulching as the most frequent source of plastic contamination in agricultural soils. Generally, the plastic types used for mulching are LDPE, LLDPE, and HDPE, with a thickness between 10 and 80 µm. These plastics may be single or multiple-span of different colors (transparent, white, black, and white-on-black, etc.).In mulching, a large volume of harmful residues of plastics is observed on the surface and subsurface of farmlands because the polyethylene materials that compose the mulch plastics do not degrade rapidly in the soil and the collection of all waste residues is not possible. In European Union countries, 100,000 tons of plastics are used annually for mulching, but only 32% of this amount is collected at the end of the farming period; the remaining plastic is burned or landfilled in soils [5]. For instance, microplastic residues were found in all three layers of maize mulch farmlands in China [35]. Likewise, Liu et al. [46] reported 78.00 ± 12.91 items/ kg of microplastic in the mulch soils of the suburbs of Shanghai. Huang et al. [47] disclosed that microplastic residue abundance in the mulch farmlands increased over time as the farmlands that have been in mulch for 24 years contained 13 and 3 times more microplastics than 5 and 15 years, respectively. Greenhouse farming is another source of microplastics [36], with 250,000–350,000 tons/year of microplastics used in greenhouse farming per year [15]. Large amounts of plastic waste (mostly LDPE and EVA) are generated because plastic film usually lasts 2–3 years [3]. Saadu and Farsang [36] reported 225 ± 61.69 pieces/ kg of microplastics in the two layers (0–20 cm and

20–40 cm) of greenhouse farmland in southern Hungary. Similarly, Zhang and Liu [48] reported 18,760 particles kg^{-1} in the Chai Valley of China. The abundance of plastics contaminants in the mulch and greenhouse farmlands is related to the duration of application of plastics materials as well as the influence of climate (temperature, solar radiation, precipitation, and wind). Another critical factor that results in the early aging and degradation of plastic films is the level of agrochemicals. Agrochemicals most used contain a chemical compound of halogen, sulfur, and chlorine that cause easy decomposition of plastic films [15]. All these factors caused the fragmentation of larger plastic contaminants.

Plastic contamination in agricultural soils is also climate-related [49]. For example, contamination occurs via atmospheric and wind deposition, flooding, irrigation, runoff, and surface littering. Precipitation and snow melting also wash suspended microplastic particles into the soil [50]. Furthermore, wind erosion transports and deposits microplastic materials from their source to the soil [7].

Abundance of microplastics in agricultural soils

Table 1 shows a summary of the abundance of plastics detected in the agricultural soils of various countries in studies from 2020 onwards. As expected, the soil is a significant recipient of agricultural plastics, although the abundance and composition of plastic contaminants differ spatially and temporally. This variation is caused by factors such as the rate of plastic consumption, duration of plastic usage, and inconsistencies in the sampling techniques and laboratory analysis. However, based on these data, microplastics are found in many agricultural soil types, including the soils on arable land [51], paddy land [22], uplands [52], irrigation areas [53], and greenhouse farmland [54, 55]. Although plastic contaminants are found at various soil depths and profiles, the concentration of contaminants is the highest in the surface layer of agricultural soils [51, 56]. For example, Sa'adu and Farsang [55] recorded 300 ± 93.09 and 150 ± 76.37 pieces kg^{-1} at two different depths of greenhouse soil in southeastern Hungary. Similarly, Schothorst et al. [43] found 2242 ± 984 and 888 ± 500 microplastics kg^{-1}, respectively, at soil depths of 0–10 and 10–30 cm in the agricultural soil of Spain and the Netherlands. Based on the plastic sources detailed in Table 1, two are the main pathways through which microplastics enter agricultural farmlands: sewage sludge and mulching. For example, Tagg et al. [51] detected 14.6 microplastics g^{-1} in the soil in Germany, mainly due to the high content of microplastics in sewage sludge. In addition, Li et al. [57] found 8885 and 2899 pieces of microplastic kg^{-1} in shallow and deep soils treated with maize mulch in China.

Units of macroplastic and microplastic measurement

The use of a uniform unit of measurement across studies is helpful because it allows exact plastic pollution values to be compared. Different measurement units are used in different regions to measure plastics in agricultural soils. To assess macroplastics, centimeters, square centimeters, and kilograms per hectare are often used [35, 36, 47]. To assess microplastics, units such as millimeters, micrometers, and nanometers and their associated squared units are used [35]. The quantity of plastic contaminants is also measured in units such as milligrams per kilogram, particles per gram, particles per kilogram, and items per square meter [17, 18, 43, 58, 59]. These units are used interchangeably with other units, such as items per kilogram and pieces per kilogram [37]. There is a need to standardize units to ensure that values can be compared without difficulty across studies of plastics.

Soil sampling

Sampling is the selection of a subset of elements from the total population that provides information about the general properties of the area under consideration and circumvents the impossibility of collecting data on the total population [60]. Accordingly, many contaminated soil samples can be collected to determine soil contamination levels. Correct knowledge of an area is vital as it can provide preliminary information on contaminant distribution and hotspots and inform the choice of a sampling method. Quality research is determined by the quality of sampling and sampling methods. Sampling quality also depends on the sample number related to the sampling coverage area.

Many microplastic sampling techniques have been used in agricultural soils (e.g., point and mean sampling strategies), and almost all types of sampling strategies apply to studying macroplastic and microplastic contamination. The sampling technique depends on the type of research, nature of the contamination, geomorphology, research objectives of the study, and potential contaminant sources. In the literature reviewed here, the transect field technique was used the most to sample microplastics in agricultural soils [35, 38, 44, 49, 58]. The second most frequently used sampling technique was random sampling [22, 41, 43, 48, 61]. A combination of two or more sampling techniques may be used depending on the nature and spatial distribution of the contaminants in the field. Mixed-method soil studies can be used to collect missing data from sampling sites. Archival soil data collected and efficiently stored in the past are also used in microplastic studies. For instance, Corradini et al. [62] used soils sampled 4 years prior to their study, quantifying the level of microplastics in regional-scale soils under different land use conditions. The abundance of

Table 1 Abundance of microplastics in agricultural soils

Country	Plastic source	Soil type	Crop(s)	Abundance		Composition	References
				Macro	Micro		
Hungary	Greenhouse	Arable land	Tomatoes	6.4 kg h^{-1}	225 ± 61.69 pieces kg^{-1}	PE, PVC, and PP	[36]
China	Mulch	Arable land	Maize	6796 ± 1070 pieces m^{-2}	8885 and 2899 pieces kg^{-1}	PE, PP, and PET	[57]
China	Mulch	Upland land	Maize		754 ± 477 items kg^{-1}	PP, PE, PET, and PES	[52]
China	Sludge	Paddy land	Rice and wheat		149.2 ± 52.5, 68.6 ± 21.5, and 73.1 ± 15.4 particles kg^{-1}	PES, PP, and PS-AC	[22]
China	Plastic gauze	Arable land	NA		1629.68 tons $year^{-1}$	NA	[26]
Japan	Coated fertilizer	Paddy land	Rice		144 mg kg^{-1}	PE	[37]
Thailand	Mix	Mix	Cabbage, pumpkin, guava, etc.		12–117 items m^{-2}	PE, LDPE, PP, and PS	[59]
India	Mulch	Arable land	Tomatoes		37.97%, 35.07%, and 36.99% plastic residue	NA	[61]
Korea	Mix	Mix	Rice and vegetables		664 pieces kg^{-1}	PE and PP	[66]
Switzerland	Mulch	Drainage water	Vegetables		10.5 ± 9.5 N L^{-1}		[70]
Germany	Sludge	Arable land	NA		14.6 MP g^{-1}	PES, PA, PVC, PAN, etc.	[51]
Greece	Film	Greenhouse	Watermelon and tomatoes		301 ± 140 and 69 ± 38 items kg^{-1}	PE and BMF	[54]
Spain and Netherland	Mix	Mix	Broccoli, celery, and watermelon		2242 ± 984 and 888 ± 500 MPs kg^{-1}	NA	[43]
Switzerland	Organic compost	Arable land	NA		22.4 ± 3.3 tons $year^{-1}$	NA	[71]
Tanzania	N.A	Irrigation land	NA	0.5–5.5 kg	0.21–1.50 items g^{-1}	PET, HDLE, LPE, PS, etc.	[53]
Mauritius	Mix	Arable land	Vegetables		320.0 ± 112.2 and 420.0 ± 244.0 particles kg^{-1}	PP and PA	[56]
Tunisia	Mix	Mix	NA		13.21 ± 0.89 to 852.24 ± 124.2 items kg^{-1}	PEVA, PE, PBAT, and PP	[25]
Chile	Mix	Mix	NA		306 ± 360–184 ± 266 particles kg^{-1}	PE, PP, and PS	[62]
Canada	Biosolid	Arable land	NA		4.1 × 1011 and 1.3 × 1012 particles	PE, PP, PS, etc.	[58]
Mexico	Mulch	Arable land	NA		400–2000 particles kg^{-1}	LDPE	

NA not applicable

microplastics differs from one point to another due to differences in land management, soil, geomorphology, depth, etc. To overcome heterogeneity, samples from different sub-units within a sample site may be harmonized and formed a composite, creating proper representation, and reducing the number of samples. Saadu and Farsang [36] applied composite sampling techniques and harmonized the samples of different layers of soil profiles in the greenhouse farmlands of southern Hungary.

The number of samples required in plastic contamination studies on agricultural farmland depends on the size of the farmland, the source of agricultural plastic, and the budget and aim of the study. Several soil sampling points are used in effective studies, e.g., many samples (0.5–1.0 kg) are usually collected to provide sufficient sample numbers for treatments and replication. In vertical contamination assessments, soil depth and profile are important. The depth of a sample depends on the methods and duration of plastics application methods, farmland management practices (such as tillage and plowing), and objectives of the study. The period of agricultural soil amendment with compost and sewage sludge containing plastic fragments determines the sampling period and differences in the plastic content of the soil [58].

For macroplastic sampling, several experimenters collect visible plastic materials from the surface of the study area [35, 38]. Macroplastic materials in agricultural farmlands are gathered where mulching films have been installed and buried at 0–40 cm [35, 47] and in greenhouse farmlands [36]. In the present review, the examined studies showed that soil microplastic contaminants were collected at different soil depths as follows: 0–5 cm [63], 0–10 cm [7, 8, 49], 0–15 cm [37, 58], 0–20 cm [59], and 0–30 cm [17, 18, 35, 41, 43, 61]. Most studies included soil sampling at 0–30 cm. The soil depth used depends on the nature of the plastic materials used, soil management techniques (e.g., plowing and harrowing), and soil physical and chemical properties (e.g., leaching and hydraulic conductivity and infiltration capacity). Some studies of microplastic contamination in the soil profiles and groundwater included sampling at a depth of a few meters [36, 64].

Soil characterization: soil organic matter, clay, and sand content

The characterization of soil's physical and chemical properties is critical in studies on plastic contamination. Information on some parameters, such as soil organic matter (SOM), clay, and sand content, directly affects sample preparation techniques (e.g., drying, sieving, soil aggregate dispersion, and organic matter digestion), selection of salt types, and saturation level of salts used in density separation [33, 34]. Microplastic extraction quantities from the soil depend on the soil's texture. Yu et al. [17, 18] and Watteau et al. [65] found that the presence of soil microplastics was associated with soil texture. For example, more microplastics are recovered in sandy soils than in clay soils. The clay and organic matter content in agricultural soils make microplastic extraction difficult because the micro-sized clay particles are mixed with the soil matrix, which hinders the proper identification and quantification of microplastics in these soils [34, 45]. However, the predigestion and postdigestion of organic matter increase the recovery rate of microplastics. Conversely, sandy soils have a large grain size that facilitates the separation of microplastics and other substances from soil particles. The large pore spaces in sandy soils help provide insights into the penetration of contaminants into the soil horizon.

Sample processing: drying, sieving, and soil aggregate dispersion

Soil from agricultural farmland is usually processed before analyzing and extracting microplastic and macroplastic materials. Drying is typically performed to improve the precision of soil sample measurements. Soil can be dried via oven drying and surface drying. Drying time depends on the moisture content of the samples and set temperature, which is usually recommended as ≤ 40 °C to prevent damage and alterations to the plastic particles. Nevertheless, soil samples were dried at different temperatures for different durations in the reviewed studies. For example, 40 °C for 5 days was used by Sa'adu and Farsang [55], 60 °C for 48 h was used by Choi et al. [66], and 70 °C for 24 h was used by Liu et al. [46]. One advantage of drying is the reduction of soil sample contamination by microplastic fibers suspended in the air, whereas the main disadvantage is the destruction of plastic materials at a high temperature. Drying is still achieved in some cases by spreading and air drying the soil samples (e.g., [47], however, environmental, and atmospheric contamination is more likely following this drying method. Wet sieving is conducted when large sample volumes are collected, and drying is not required. The samples are processed directly using water to reduce sample size and discard particle sizes that are not required in the analysis [38].

Soil aggregate dispersion

Plastic contaminants are sometimes attached to the soil matrix to such an extent that their removal is only possible via the dispersion of soil particles. Such dispersion can be achieved using various means, but the application of dispersion methods in microplastic extraction studies is challenging because the process can change the plastic materials' form, shape, and size. A simple method in which tap or distilled water is added is used during sample reduction to create dispersion [38]. Dispersion can also be achieved by shaking the solution in orbital shakers [44]. The use of dispersion agent chemicals, such as an aqueous sodium hexametaphosphate solution, can have similar effects [33, 67]. Mild grinding using a ceramic mortar and pestle, which does not destroy the plastic particles, can be also used to break soil clods [34, 42, 55, 61]. Additionally, ultrasonication [22, 45] and pressurized mobile-phase leaching can effectively destroy soil aggregates and create soil dispersion.

Digestion/SOM removal

Soil management, such as amendment with organic fertilizers, can lead to excess SOM content in agricultural soils. Organic matter is higher in agricultural soils than in sediments and sands [34]. The SOM in agricultural soils is problematic in microplastic contamination studies because it has a similar weight and density to most plastics [31]. Thus, density separation is performed to separate soils from microplastics because the presence of SOM can interfere with the results of the microplastic analysis. SOM can be removed from the soil using acidic methods in which an acidic solution, such as nitric or sulfuric acid, is used to digest SOM. Alkaline methods involving the use of KAOH or NaOH are also used for digestion. Other digestion methods include the use of oxidation reagents, such as Fenton's reagent and H_2O_2 [63]. Enzymatic methods have also been attempted with success. An oxidation method in which H_2O_2 is used to digest SOM was employed in several of the studies reviewed [22, 47, 59, 61]. This method is adopted because it does not destroy the structure or morphology of the microplastics and achieves a recovery rate of > 90%.

Density separation: water, $ZnCl_2$ $NaCl_2$, and NaI

Density separation is an important step in the microplastic analysis. This method aims to exploit the buoyancy of the plastic materials on the surface of supernatants. It works on the principle that a high-density solution usually has a higher density than that of the average density of plastic materials. The minimum density of plastic in agricultural soils is 0.9 g cm^{-3} (PP), whereas the maximum density is 1.65 g cm^{-3} (40% polyphenylene sulfide) (http://www.polymerdatabase.com/). In density separation, the soil sediments settle down owing to their high density, whereas the microplastics and other materials float on the surface. Standardized density separation methods for microplastic analysis in the soil have not been developed. In addition, extraction procedures differ in terms of the technical setup, extraction duration, and quality and amount of salt added to the solution [33]. Different types of density separation medium were used in the microplastic contamination studies reviewed here: distilled water [44], NaCl [22], NaI [34], ZnCl [36], NaBr, CaCl, and sodium heteropolytungstate solutions [33]. Corradini et al. [62] combined two or more density separation techniques to achieve high levels of extraction. The separation technique chosen depends on the type of plastic polymer studied and aims of the study. Studies that aim to extract high-density plastic fragments (e.g., PVC and PET) use high-density salt solutions (NaI and ZnCl), whereas studies that target low-density microplastics (e.g., PP, LDPE, medium-density polyethylene, and HDPE) use distilled water (1.0 g cm^{-3}) and NaCl (1.2 g cm^{-3}) [55]. The availability, low cost, and environmentally friendly nature of low-density separation mediums, such as distilled water and salt, have facilitated their frequent use in microplastic studies. Two to three rounds of density separation using these methods are usually recommended to remove microplastic materials efficiently. Other salt solutions that are promising for the density separation of both low- and high-density plastics include NaI (1.6–1.8 g cm^{-3}), ZnCl (1.5–1.7 g cm^{-3}), NaBr (1.4–1.6 g cm^{-3}), and CaCl (1.3–1.5 g cm^{-3}). These salts can be used to extract microplastics with a high efficiency rate, but some of the main challenges include their availability, associated costs, and environmental contamination. Li et al. [34] compared three different salts (NaCl, ZnCl, and NaI), concluding that NaI and ZnCl are suitable for separating fibrous and high-density materials but have no beneficial effect on fragments and bulk microplastics, whereas NaCl was recommended for low-density microplastics. Similarly, Sa'adu and Farsang [55] concluded that distilled water and NaCl efficiently remove low-density plastics.

Filtration

The salt and suspended microplastic solution are separated via decantation and filtration using filter paper. The separation of microplastics from soil sediments can be achieved via decantation, whereby the upper supernatant is collected using a pipette, after which the supernatant is filtered using a filter with a vacuum pump. The filter types used for microplastic extractions in the reviewed studies included Whatman No. 40, grid-line membrane, cellulose acetate, glass fiber, nylon fiber membrane, and quartz filters, and these filters had pore sizes of 0.22 µm–1.00 mm [22, 42, 45–47, 62, 66]. However, the type of filter was found to affect the number of microplastics recovered from the soil. For example, [34] compared different filters and concluded that optimal microplastic extraction relies on passing the solution through nylon filters. The filter type depends on the study's objectives and targets. For example, filters with small pore sizes are used in studies that aim to extract small microplastic particles. However, solutions containing sediment particles are unsuitable for use with filters with small pore sizes because this causes clogging that slows down the filtration process. Such problems can be resolved by replacing clogged filters, and both the original and new filters are stored and used to quantify microplastic content. Different filter sizes are also recommended because microplastics with large surfaces cover those with smaller surfaces and affect the total count of microplastics. To prevent the loss of sample portions that stick to the containers and sample contamination, washing the walls of the microplastic receptacle and using tweezers to pick up microplastic particles and filters is recommended.

Visual sorting via microscopy

The visual identification of plastic materials is arguably the most crucial process in microplastic studies [31]. Macroplastic materials can sometimes be identified using the naked eye, although tiny materials must be observed using microscopes. Microplastics can easily be separated from nonplastic materials according to their sharp geometrical shape, shining surface, and intense colors. However, the characteristics used for microplastic identification can lead to errors and over-estimations of microplastic counts; thus, a sample of suspected plastic materials should be subjected to further examination via heat and a needle, wherein the needle is heated to attain a minimum temperature that changes the shape of the microplastics. This method is performed under a microscope, and the microplastic materials' surface changes are easily observed.

Spectroscopy

Because of the complexity and homogenous nature of plastic contaminants with other contaminants, plastic materials are usually validated via further examination. The exact polymer type of the materials must always be confirmed after the plastic materials are visually identified. Numerous methods are used to characterize polymers, but only Fourier-transform infrared (FTIR) and Raman spectroscopy are considered in this review as they were applied in the reviewed studies. In FTIR spectroscopy, an interference wave interacts with the sample in contrast to a dispersive instrument, and the interacting energy assumes a well-defined wavelength range [68]. Each molecule or chemical structure produces a unique spectral fingerprint, making FTIR analysis an excellent tool for chemical identification. FTIR spectroscopy is currently the most popular approach for characterizing microplastics. Attenuated total reflectance (ATR)-FTIR and microscopy-coupled FTIR can be used to measure particles with sizes of 20 mm to > 20 µm, depending on the composition and molecular structure of the substance. The technique is nondestructive but is not appropriate for analyzing samples with sizes of < 20 µm [61]. FTIR techniques have been applied to analyze the agricultural soils of various regions [38, 40, 47]. In the review of Veerasingam et al. [69], ATR-FTIR was found to have been used in 60% of studies to analyze samples and characterize different polymer types for various environmental matrices. Raman spectroscopy is another sensitive method used to characterize polymers. After the samples are subjected to Raman rays, Raman spectra are usually generated and compared with a library to identify the exact composition at a certain percentage. This technique has many advantages and is ideal for measuring the polymer composition of small samples, although refinements are required prior to analysis.

Conclusion

The study of microplastic contamination in agricultural soils is increasingly attracting the attention of researchers and decision-makers, given the harmful effects of microplastics on the soil ecosystem. In this review of the most recent literature, plastic contaminants were found to enter agricultural soils via several sources, but mainly through the application of mulch and sewage sludge. However, Table 1 summarizes the current knowledge on microplastic abundance in agricultural soils. The table shows that microplastics with an abundance between 210 pieces kg^{-1} and 2000 pieces kg^{-1} have been found in different agricultural soils of different farming types. Also, microplastics can be transferred between soil areas via physical, chemical, and biological processes and climatic factors, such as wind and heavy precipitation. The presence of microplastics as pollutants has detrimental effects on the soil, surface, and underground water resources; thus, such pollution threatens human health and food security. Considering the literature on microplastics, it is essential to conduct more research in the following areas:

1. Investigations of microplastics in groundwater and the soil profiles of agricultural soils contaminated via various plastic sources, including sewage sludge, fertilization, compost application, and plastic-cover farming.
2. Determination of the presence of microplastics and nanoplastics in agricultural soils and edible products, such as leaves, roots, and stems plants.
3. Studies on microplastic contamination in environments with different land use patterns.
4. Development of best practice solutions for reducing plastic pollution in agricultural areas.

Abbreviations

MaP	Macroplastics
MiP	Microplastics
NaCl	Sodium chloride
ZnCl	Zinc chloride
NAI	Sodium iodide
LDPE	Low-density polyethylene
PVC	Polyvinyl chloride
EVA	Ethylene vinyl acetate
LLDPE	Linear low-density polyethylene
HDPE	High-density polyethylene
PET	Polyethylene terephthalate
PP	Polypropylene
PU	Polyurethane
PS	Polystyrene
WWTPs	Wastewater treatment plants

SOM	Soil organic matter
NaOH	Sodium hydroxide
KOH	Potassium hydroxide
NaBr	Sodium bromide
CaCl	Calcium chloride

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