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Microplastic pollution in Farmland soils: A review on types, sources, analytical methods, environmental and human health risks

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Abstract

Microplastics (MPs) are emerging pollutants of growing concern in the environment. Initial studies on MPs occurrence, detection and risks have been extensively studied in the aquatic environment, far less of their occurrence and fate in agricultural ecosystems. Based on existing studies, this paper first focused on MPs types and sources. Secondly on the analytical approaches for soil MPs and emerging technologies. Furthermore, growing evidence of MPs threatening food security and human health was studied and risks posed by soil MPs to the environment and human health. Future research directions were outlined including standardized protocols for identifying and quantifying MPs, extensive human health risk assessment of soil MPs, synergistic and additivity effects of adsorbed chemical cocktails, the need for legally binding global legislation and a call for better management of plastic wastes for the sake of food security.

Keywords: Microplastics; Soil pollution; Farmland soils; Analytical methods; Health risks

Introduction

Microplastics (MPs) are tiny scale plastic fragments with a diameter of less than 5 mm (Okeke et al. 2023, Wu et al. 2019). They are a result of weathering, degradation and ultraviolet exposure of plastics in the environment (Guo et al. 2022). We live in a plastic age due to their benefits which include cost-effective, durability and malleability (Geyer et al. 2017, Himu et al. 2022). The global plastic production was approximately 400 Million tonnes (Mt) in 2019 (Khan et al. 2022, OECD, 2022). Only a low percentage of plastics are recycled while the rest end up in the environment including landfills (Yu et al. 2022). Microplastics have been a major environmental concern over the last years due to their widespread and the risks they pose to the environment (Ding et al. 2020).

Past studies on microplastic pollution have investigated heavily on marine environments (waterbodies and ocean) (Andrady 2011, Bellasi et al. 2020, Biginagwa et al. 2016, Jambeck et al. 2015, Kataoka et al. 2019, Khan et al. 2020, Shilla 2019). Soils are no longer pathways but sinks for these particles (Fakour et al. 2021, Yu et al. 2022). The abundance of microplastics in terrestrial environments is believed to be 4 to 23-fold than that in the ocean (Feng et al. 2020, Li et al. 2020, Yu et al. 2022). The increase in population and level of urbanization has significantly contributed to the contamination of soil with emerging pollutants reducing soil productivity and fertility (Kataoka et al. 2019). Moreover, several operations including the utilization of plastics in the agriculture sector through using plastic storage tanks, drip irrigation pipes, and plastic storage containers pose a greater risk of contamination (Iqbal et al. 2023). These plastics not only alter soil physicochemical properties but also adsorb chemical cocktails that can progressively accumulate in the food chain posing a threat to food and human safety

(Guo et al. 2022, Huang et al. 2021, Perković et al. 2022).

By 2050, it is estimated that with current production and collection techniques about 12,000 Megatons will be deposited in soils and other ecosystems (Geyer et al. 2017). Therefore, mitigation measures are essential. However, due to lack of research on MPs occurrence in terrestrial ecosystems (He et al. 2018, Huang et al. 2021, Huerta Lwanga et al. 2016, Rillig 2012). Urgent focus is needed on types, sources and methodological approaches amidst new emerging protocols. In addition, MPs in soils raise food safety concerns as they can result in potential health hazards. This underscores the need for comprehensive data on environmental and human health risks associated with soil microplastics. Addressing these issues is paramount to safeguarding terrestrial ecosystems and imposing a focus on mitigation strategies amidst increasing microplastic contamination.

Thus, this review aims to compile and synthesize findings from existing studies to provide comprehensive review of microplastic contamination in farmland soils. By identifying types, sources, detection, environmental and human health risks. The review will also highlight the known toxic effects and speculative risks of soil MPs to human health and offer applicability of new methods from other scientific fields about MPs research.

Types of resins occurring in farmland soils

The information about the type of resins in farmland soils is not only crucial for providing the basis for cleanup but also for influencing policymakers in structuring legislation that restricts the use of certain resins. Moreover, it helps in managing soil MPs in the terrestrial environment. Distribution of MPs types in farmland soils is said to be narrower compared to that in freshwater environments. For instance, Koutnik et al. (2021) reviewed several studies and found that nearly 80% of them detected Polyethylene (PE), Polypropylene (PP), and Polyethylene Terephthalate (PET) in soil samples. This is because these types of plastic are commonly used, indicating a relationship between plastic production and the presence of microplastics in soil. Ding et al. (2020) discovered PE, PP, PET, Polystyrene (PS), high-density polyethylene (HDPE), and Polyvinyl Chloride (PVC) in agricultural soils of Shaanxi province. Fakour et al. (2021) identified Low-density Polyethylene (LDPE) and PS as major polymers in the studied farms. Himu et al. (2022) discovered the dominance of Acrylonitrile butadiene styrene (ABS) and Polycarbonate in rural farmlands and the prevalence of LDPE, PP, HDPE, and PET in sub-urban farmlands in Central Bangladesh. The occurrence frequency of plastic resins indicates that PE (including, HDPE and LDPE), PP and PET as the most frequently detected polymers in soil samples as they are mostly used commodity plastics commonly for packaging (Table 1).

Table 1: Plastic Resin types detected in farmland studies

Authors	**Plastic resin types**								
	PVC	**PP**	**PET**	**PS**	**PE**	**HDPE**	**LDPE**	**PC**	**ABS**
Himu et al. (2022)	-	√	√	-	-	√	√	√	√
Ding et al. (2020)	√	√	√	√	√	√	-	-	-
Fakour et al. (2021)	-	-	-	√	-	-	√	-	-
Feng et al. (2020)	-	√	-	√	√	-	-	-	-
Liu et al. (2018)	-	√	-	-	√	-	-	-	-
Kundu et al. (2021)	-	√	√	√	-	-	-	-	-
Hao et al. (2023)	√	√	√	-	√	-	-	-	-
Koutnik et al. (2021)	-	√	√	-	√	-	-	-	-
Occurrence frequency	2	7	5	4		9		1	1

Sources of MPs in farmland soils

The bigger issue of plastic use and inputs of plastics in agricultural production has led to microplastics in soils (Tang 2023). Over-use, advancement of technology through the use of plastics in agriculture (Plasticulture) and uncontrolled management practices have resulted in increased buildup of plastics in soils. MPs enter farmland soils through agricultural operations and depending on their origin, MPs can be classified as primary MPs, which are micro-sized plastic particles used as raw materials for commercial productions like cosmetics (Andrady 2011, Wang et al. 2022). Primary MPs gain entry into farmland soils through sewage irrigation, application of compost and biosolids and use of polymer-based slow-release fertilizers (Iqbal et al. 2023). Secondary MPs are produced as a result of larger plastic materials wearing and tearing down due to the influence of environmental forces such as wind, light, high temperature and soil organisms (Iqbal et al. 2023). Secondary MPs from farmland soils emerge from the breakdown of agricultural plastics including drip irrigation pipes, plastic silage, mulch film, plastic packaging from fertilizers and pesticides and all abandoned plastic products in the soil (Wu et al. 2019) (Figure 1).

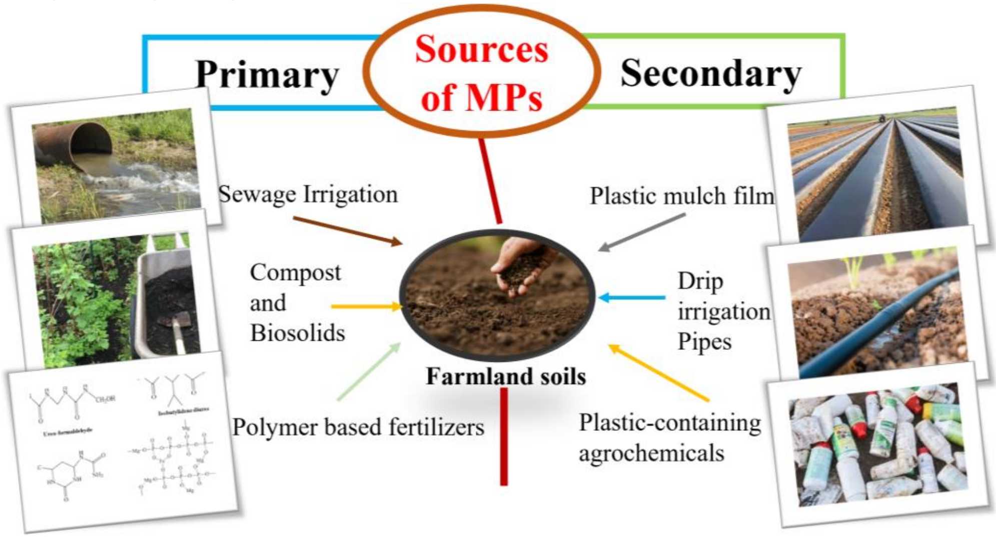

Figure 1: Sources of MPs in Farmland soils with modifications from Iqbal et al. (2023)

There are multiple sources of microplastic pollution in farmland soils for instance Liu et al. (2018) was among the first studies to investigate microplastic occurrence between shallow soils (0-3 cm) and deep soils (3-6 cm) and link contamination of soils with plastic mulching. Piehl et al. (2018) found that onsite degradation of macroplastic debris was among the source of MPs in farmland soils of Southeast Germany with an average value of 0.34 ± 0.36 MPs/kg dry weight (DW). Himu et al. (2022) agree with Piehl that MPs in farmland soils are linked to poor management of plastic wastes although the author's study found the greatest number of MPs in small villages and towns. Fakour et al. (2021) aligns with Liu et al. (2018) that plastic mulching causes MP contamination in soils and concluded further that MPs abundance in farms are not only from direct agricultural sources but also due to tire tread particles and plastic debris from buildings and residential areas.

It was also highlighted that the application of plastic mulch, historical land use and utilization of fruit protective foams as the main sources of MPs in farmland soils of Tainan city. The distribution differs with land use. Hao et al. (2023) discovered that road traffic, organic fertilizer and multiple cropping index as sources of MPs in the Taihu Lake region in China. Despite the contributions of these studies in identifying multiple sources of MPs in soils most of them focused only on surface soils which limits understanding of transport mechanisms, degradation and their effects on the subsurface environment

Determination of MPs concentration in soils

Sampling strategies

Soil sampling is an essential step in microplastic study to achieve accurate and reliable results. Depending on the research purpose, the method's economic proportionality and the study compartment different sampling techniques may be employed (Razeghi et al. 2021). Judgmental, random, composite, systematic, unaligned grid, transect and stratified sampling are all viable sampling methods for MPs (Junhao et al. 2021, Möller et al. 2020). Most important is to take account of past plastic usage, direct and indirect sources of plastics, the location of the field including nearby roads and a sufficient number of samples (Chia et al. 2024). Random sampling guarantees an equal chance of being chosen hence preventing bias. Systematic sampling ensures uniform coverage in the field with sampling points forming a known pattern (Junhao et al. 2021). Transect sampling entails taking samples at predetermined intervals along one or more straight lines that are not necessarily parallel while stratified sampling identifies substantial changes between soil layers (Möller et al. 2020).

Weber et al. (2021) agree with Möller but conclude that systematic sampling techniques as the feasible option for sophisticated research due to the heterogeneity properties of soils. Sa'adu and Farsang (2023) coincide with Möller and Junhao but also added in their review that the most common sampling methods used for agricultural soils are Transect sampling followed by Random sampling. Chia et al. 2024 was inconsistent with findings from Sa'adu and Farsang (2023) about the most common sampling method. Chia et al. (2024) claims that random and composite sampling is most common due to its simplicity and affordability. They both agreed that a combination of two or more sampling methods guarantees more sampling accuracy depending on the nature and spatial distribution of contaminants in the field which was also raised by Junhao et al. (2021). Seo et al. (2025) also agreed that combining two sampling strategies improves reliability however, states that composite samples with random sampling or unaligned grid sampling may more appropriately represent MP contamination of a target field. This is because a single-point sample is inappropriate as MPs can be distributed randomly in a soil matrix. Microplastics in farmland soils are unevenly distributed due to various reasons including foreign inputs, soil properties and the physical and chemical properties of the plastics themselves (Wang et al. 2022). According to Chia et al. (2024), one should resort to composite sampling when resources are limited and blend well with a zigzag sampling pattern instead of random sampling. A minimum of ten samples are recommended for a composite sample. Table 2 summarizes the different sampling techniques and sources of soil MPs from different studies.

Table 2: Sampling strategies and sources of MPs in farmland soils.

Location	Sampling strategy	Source	Reference
Shanghai, China	Stratified	Plastic mulching	(Liu et al. 2018)
Franconia, Germany	Transect	Onsite degradation of macroplastic debris	(Piehl et al. 2018)
Mellipilla, Chile	Random	Successive sludge applications	(Corradini et al. 2019)
Hangzhou Bay, East China	Random and Composite	Irrigation water and plastic mulch	(Zhou et al. 2020)

Tibean plateau, China	Random	Facility agriculture and previous secondary industry	(Feng et al. 2020)
Shaanxi Province, China	Random	Irrigation with wastewater and sewage sludge application	(Ding et al. 2020)
Tainan, Taiwan	Area	Plastic mulch, historic land use, plastic packaging, fruit protective foams	(Fakour et al. 2021)
Arusha, Tanzania	Random and Composite	Surface water irrigation	(Kundu et al. 2021)
Dhaka, Bangladesh	Transect	Poor management of plastic wastes	(Himu et al. 2022)
Shouguang City, Shandong Province	Random and Composite	Plastic mulch films, flooding and fertilizer	(Yu et al. 2021)
Taihu Lake, China	Random and Composite	Organic fertilizers, multiple-cropping index, road traffic	(Hao et al. 2023)
Dar es Salaam, Tanzania	Transect	Surface water irrigation and organic fertilizer application	(Kato et al. 2024)
Viseu, Northern Portugal	Random and Composite	_	(Rede et al. 2025)

MPs separation techniques in soils

Separating microplastics from soil is a difficult and important step in analyzing MPs. There is currently no established method for separating MPs from soil matrices, but various methods from previous studies have been used such as centrifugation, wet sieving, and density separation (Ding et al. 2020, Fakour et al. 2021, Feng et al. 2020, Himu et al. 2022), continuous airflow (Hao et al. 2023) and oil separation methods (Kononov et al. 2022). Möller et al. (2020) provided a clear classification of extraction methods into manual extraction, electrostatic separation and consecutive matrix removal (Figure 2).

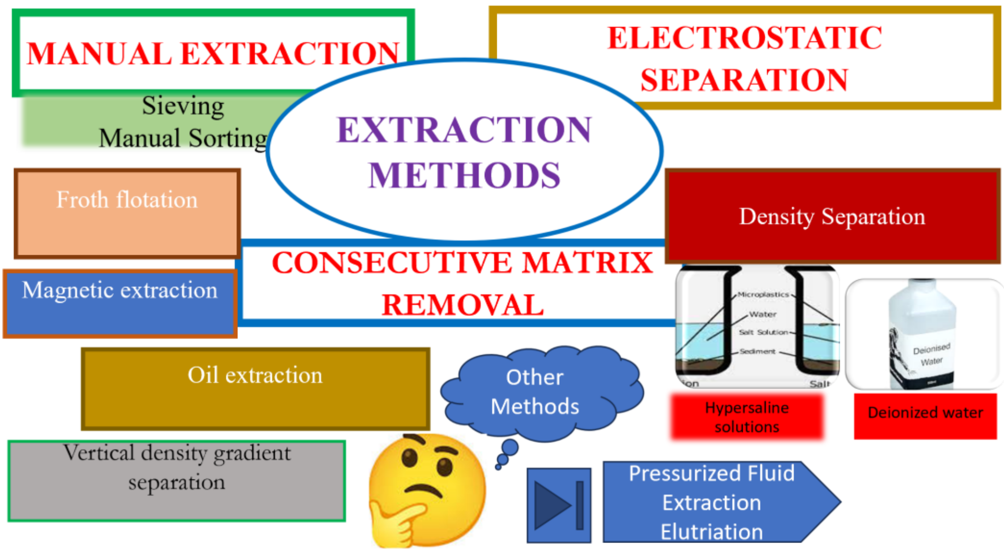

Figure 2: Extraction methods for soil MPs analysis modified from Möller et al. (2020)

Density Separation (DS)

Density separation is the most commonly utilized method for separation as it hinges on hydrophobicity property. Plastics do not absorb water and most of them float on certain aqueous solutions which is the main mechanism of density separation by using density salt solutions (Kononov et al. 2022, Thomas et al. 2020). Hypersaline solutions involve exploiting differences in the density of plastics and salt. Since densities differ of most common microplastics ranging from 0.8-1.4 g/cm^3. However, the selection of a solute depends on the type of microplastics under study. NaCl (ϱ =1.2 g/cm^3) has been quite effective for low-density polymers and is most utilized for density separation due to its low cost and environmentally friendly nature (Junhao et al. 2021). High-density polymers demand higher-density solutions such as $ZnCl_2$, $ZnBr_2$, NaI, NaBr and $CaCl_2$ for removal (Huang et al. 2021). However, most of the solutions including $CaCl_2$, NaBr, $ZnCl_2$ and $ZnBr_2$ are environmentally hazardous and toxic while NaI is deemed effective in removing MPs but expensive to be utilized (Kononov et al. 2022). Other studies have employed the mixing of NaCl and $ZnCl_2$ to extract MPs and it is believed to yield higher density and lower cost than using pure salt only (Corradini et al. 2019, Seo et al. 2025). Centrifugation has been considered to shorten the time of density separation, although high centrifuge speed may cause damage to MPs. Therefore, effective separation of MPs without risk of fragmentation may require a balance of centrifuge speed. DS is employed in numerous studies yet it lacks green chemistry principles which is a key aspect of the 2030 Sustainable Development Agenda. A greener analytical method is imperative for quantifying MP in soils.

Table 3: Separation methods of MPs in farmland soil studies

Location	Separation method	Recovery rate	MPs separated and identified	Reference
Shanghai, China	DS using NaCl solution	90%	PP, PE, PES	(Liu et al. 2018)
Franconia, Germany	Soaking with deionized water	-	PE, PP, PS	(Piehl et al. 2018)
Mellipilla, Chile	Wet extraction technique using deionized water, NaCl, and $ZnCl_2$ in a ratio of 1:1 followed by centrifugation	98% LDPE, PVC	-	(Corradini et al. 2019)
Hangzhou Bay, China	Continuous air flow followed by DS using NaCl and NaI solution	75.8% - 112.4%	PVC, PE, PP, PS, PA	(Zhou et al. 2020)
Tibean plateau, China	DS using NaCl solution	-	PE, PA, PS, PP	(Feng et al. 2020)
Shaanxi Province, China	DS using NaCl and $CaCl_2$ solution	-	PS, PE, PP, HDPE, PVC and PET	(Ding et al. 2020)
Tainan, Taiwan	DS using NaCl solution	85-95%	LDPE, PS (fragments and fibers)	(Fakour et al. 2021)
Arusha, Tanzania	DS using Sodium tungstate dehydrates ($Na_2WO_4.2H_2O$)	-	PP, PS, PET	(Kundu et al. 2021)
Dhaka, Bangladesh	DS using NaCl solution	-	PE, PP, PET, PE-PP, PAN,	(Himu et al. 2022)

Shouguang City, Shandong Province	DS using NaCl solution	90%	PA, EVA, PVA, PVC, PS PE, PP, EPC, PS, PES, cellophane, PU, ABS, PMMA, Rayon	(Yu et al. 2021)
Taihu Lake, China	Continuous air-flow floatation	-	PP, PE, PET	(Hao et al. 2023)
Dar es Salaam, Tanzania	DS using $ZnCl_2$ solution	-	PE, PP, PET, HDPE, PES, PA, PVC	(Kato et al. 2024)
Viseu, Northern Portugal	-	100%	PE, PP	(Rede et al. 2025)

Oil extraction (OE)

Oil extraction is the second most common extraction method that involves removing microplastics that have infiltrated the oil layer. Oil extraction involves exploiting the oleophilic properties of plastic particles. Different oils can be used as extractants with various densities and polarity such as olive oil, mineral oil, synthetic oil, and rapeseed oil. Studies have explored the use of oil separation in extracting microplastics and have shown the applicability of oils can yield high recovery rates of MPs. For instance, Mani et al. (2019) tested castor oil and reported high recovery rates of 99 ± 4%.

Scopetani et al. (2020) tested olive oil in extracting microplastics from soil and compost samples and discovered that olive oil offers a high recovery rate of 90 ± 2% and 97 ± 5%. Kononov et al. (2022), conducted an experiment to extract microplastics from agricultural soils using canola oil and discovered that the recovery rates of LDPE and PP ranged from 95.2- 98.3% and 95.2- 98.7%. Both these studies yielded high recovery rates (>90%) in comparison to the density separation method which may cause particle loss, aggregation and adherence to container walls thus lowering MP recovery rates. The oil extraction process is straightforward, secure, affordable and efficient. However, oil residues resulting after extraction become an obstacle when used in conjunction with spectral detection (FT-IR, Raman). Thus, the oil extraction sample may require additional cleaning. Additionally, the interference of soil organic matter cannot be eliminated using this technique. Perhaps combining DS and OE would increase the efficiency of MP extraction. Future studies are required to validate and assess the oil extraction method in different soil types and necessary additional cleaning steps to improve its efficiency in MP extraction.

Digestion of MPs in Soils

Digestion is among the most challenging part of MP analysis because it involves the removal of soil organic matter (SOM) which has a similar density and weight to many plastics (Sa'adu and Farsang 2023). Therefore before analyzing, it is necessary to remove all organic matter in soils (Junhao et al. 2021). Various methods such as the use of acids, alkalis, oxidizing treatments, and enzymatic digestion were employed to eliminate soil organic matter from agricultural soils (Fakour et al. 2021, Hurley et al. 2018, Yu et al. 2021).

Hurley et al. (2018) offered a valuable assessment on the effectiveness of 30% H_2O_2, 10% KOH, 10M NaOH, and Fenton's reagent in eliminating SOM. The results showed that H_2O_2 was particularly efficient in removing SOM (recovery rate > 90%) although it slightly altered the structural morphology of PP and PE. HNO_3 digestion quickly removed SOM, however, acid and alkaline digestion can cause MP degradation, and dispersing soil aggregates increases the risk of further fragmentation of MPs. Fenton's reagent is an excellent catalyst that can accelerate the digestion process. However, it is highly sensitive to pH levels above 5-6. When exposed to these levels, it may result in the formation of iron hydroxide, which can negatively impact MP visibility (Fakour et al. 2021). It is recommended that a mixture of Fenton's reagent and H_2O_2 oxidation be used to effectively eliminate SOM, provided that the appropriate concentrations and temperature conditions are met (Hurley et al. 2018, Lee et al. 2023).

Radford et al. (2021) experimented to test the effectiveness of removing organic matter from soil. The study found that the temperature did not have an impact on the efficiency of organic matter removal in samples with high or low initial organic content. However, it was suggested that increasing the temperature could improve the removal of soil organic matter, but it should not exceed 50°C to avoid damaging common microplastics. The impact of time on soil organic matter removal requires further evaluation, but prolonged exposure to 30% H_2O_2 may cause some polymers to fragment, so exposure time should be shortened as much as possible. Some studies have utilized H_2O_2 oxidation to reduce reaction time by increasing the temperature. For instance, Ding et al. (2020) used H_2O_2 at 65ºC for approximately 12 h while Zhou et al. (2022) used 30% H_2O_2 at 70ºC for 72 h as described in Table 4.

Table 4: Removal of Soil Organic Matter in Organic rich-soil Studies

Location	Digestion method	Volume (ml)	Temp (^{O}C)	Time (h)	Reference
Shanghai, China	30% H_2O_2	-	50	72	(Liu et al. 2018)
Franconia, Germany	H_2O_2	20	-	-	(Piehl et al. 2018)
Mellipilla, Chile	-	-	-	-	(Corradini et al. 2019)
Shaanxi Province, China	H_2O_2	-	65	12	(Ding et al. 2020)
Tibean plateau, China	30% H_2O_2	50	-	24	(Feng et al. 2020)
Hangzhou Bay, China	30% H_2O_2	-	70	72	(Zhou et al. 2020)
Tainan, Taiwan	30% H_2O_2	-	-	24	(Fakour et al. 2021)
Arusha, Tanzania	30% H_2O_2 and 0.05 M Fenton's reagent	200 ml H_2O_2, 100 ml Fenton's reagent	-	5 days	(Kundu et al. 2021)
Shouguang City, Shandong Province	Fenton's reagent	-	-	-	(Yu et al. 2021)
Taihu Lake, China	30% H_2O_2	-	50	48	(Hao et al. 2023)
Dar es Salaam, Tanzania	30% H_2O_2 and Fenton's reagent	ratio of 1:1 of H2O2 and Fenton's reagent	60	24	(Kato et al. 2024)
Viseu, Portugal	30% H_2O_2	-	-	-	(Rede et al. 2025)

Analytical methods for qualitative and quantitative determination of MPs in soils

Microplastic occurrence in farmland soils is still at its initiation stage (Pérez-Reverón et al.

2022). It is necessary to effectively identify and quantify soil MPs to determine their environmental risks, distribution and plan for future remediation mechanisms (Okeke et al. 2023, Zhang et al. 2022). Different analytical methods employed for the qualitative and quantitative determination of MPs in farmland soils were reviewed. In this section, analytical methods have been divided into four major subsets: visual identification (physical characterization), chemical characterization, Thermal analysis and emerging technologies.

Physical Characterization Methods (Microscopic techniques)

Visual identification involves the use of microscopy techniques (dissect, stereo, fluorescence, atomic force, transmission and SEM). These methods are mostly utilized due to their convenience and simplicity compared to chemical characterization methods (Mariano et al. 2021, Zhang et al. 2022). However, they are time-consuming and usually prone to user subjectivity (Möller et al. 2020). Quality and magnification of microscopic techniques may hinder the clear visualization of plastic particles. It is challenging to visualize MPs and distinguish them from other materials therefore to increase the accuracy of visualization, the hot needle test is normally used as a confirmatory test that exploits the thermoplastic nature of plastics (Möller et al. 2020, Zhang et al. 2022).

Chemical Characterization methods

Chemical characterization involves the use of spectroscopic techniques such as Fourier Transform Infrared Spectroscopy (FT-IR), micro-FTIR (Coupled with Microscope), Raman spectroscopy (Mariano et al. 2021). FT-IR was introduced to overcome microscopic limitations of the identification of MPs (Okeke et al. 2023). Raman spectroscopy and FT-IR are the most often used analytical methods because of their accuracy in identifying polymer types, shape, and size and their non-destructive nature (Zhang et al. 2022). Distinguishing polymeric and non-polymeric particles solely on spectral data requires careful analysis, particularly for aged microplastics. Different environmental weathering processes such as UV exposure, physical wear, biodegradation and chemical oxidation can significantly alter the surface characteristics of MPs making them difficult to identify by spectroscopic techniques. A combination of microscopic and spectroscopic techniques tends to offer much clearer identification and quantification of MPs in farmland soils (Huang et al. 2021).

Thermal Analysis (Mass quantification methods)

Thermal analysis are promising mass-quantitative method and emerging techniques. They measure the physical and chemical properties of the polymer based on its thermal stability but they are destructive in comparison with spectroscopy like Raman and FT-IR (Möller et al. 2020). Thermal analysis uses techniques such as thermal extraction desorption gas chromatography-mass spectrometry (TED-GC-MS) and pyrolysis gas chromatography-mass spectrometry (Py-GC-MS) to identify the composition of the polymers or functional group (Guo et al. 2022). Mass quantification methods are useful for assessing microplastic contamination levels (ng/g) but are limited in their ability to determine particle size and shape. TED-GC-MS and Py-GC-MS are highly precise techniques capable of detecting microplastics at very low concentrations (ng/g), making them well-suited for small sample analyses (Perez et al. 2022). However, because microplastics are often not evenly distributed, these methods may not accurately reflect overall contamination levels. Furthermore, detecting PE with TED-GC-MS is particularly challenging due to its degradation temperature being similar to that of organic matter. To improve sensitivity and minimize matrix interference, pretreatment and chemical digestion is necessary before analysis.

Emerging technologies

Recent advancements in microplastic analysis involve the development of hybrid techniques that combine spectroscopy, imaging and machine learning for rapid and more accurate detection. For instance, hyperspectral imaging with chemometrics, vis-NIR spectroscopy with multilinear and convolutional neural network (CNN) models, and NIR spectroscopy with chemometric approaches have significantly improved the identification and quantification of MPs (Coleman 2025, Peneva et al. 2025, Seo et al. 2025). For instance, NIR spectroscopy with partial least squares discriminant analysis (PLS-DA) has detected polymers such as PE, PP, PS, PVC and PET above 0.5-1 mass%. Similarly, the total organic carbon analyzer-solid sample combustion unit (TOC-SSM) in combination with FTIR utilized by Seo et al. (2025), in agricultural soils of northern Australia yielded a high total recovery rate of 97.4% for particles sized between 300 and 600 µm. Although, such technologies mark significant progress in MPs analysis a method that follows green chemistry principles is still pivotal.

Table 5: Analytical methods used for MPs determination in soils

General Procedure	Method	Advantages	Disadvantages	Accuracy	Cost	LOD & LOQ	Limitation	Standardization issues	References
Microscopy	**Stereomicroscope**	❖ Easy and fast ❖ Identifies shapes, size and color	❖ Does not provide polymer composition results	Low	Cost effective	Detects particles > 1 mm	Lacks composition analysis	No standardized protocols	(Mariano et al. 2021)
	Transmission	❖ High resolution ❖ Can perform elemental analysis when coupled with EDX	❖ Time consuming ❖ Expensive	Low	Expensive	Nanometer-scale resolution	time-consuming and expensive	-	(Huang et al. 2021, Kalaronis et al. 2022)
	Atomic force	❖ 3D images of surface structure of polymers ❖ No need for coating samples	❖ Soil samples require further testing ❖	Low	Expensive	Nanometer-scale detection	Small sample analysis area	-	(Huang et al. 2021)
	SEM	❖ Offers surface morphology, chemical composition ❖ Rapid screening of plastics and non-plastics ❖ Detect small MPs (<200 nm)	❖ Very expensive ❖ Complex to operate	High	Very expensive	100-500 µm	Not effective for small MPs, time-consuming	No universal protocol for soil samples	(Okeke et al. 2023, Zhang et al. 2022)
Spectroscopy	**FT-IR**	❖ Non-destructive in nature ❖ Simple pretreatment ❖ No fluorescence interference	❖ Expensive equipment ❖ Time consuming ❖ Cannot detect ultrafine particles	Moderate	Expensive	10-20 µm	Requires clean sample, long analysis time	No standard extraction for soils	(Guo et al. 2022)
	Raman	❖ Detect small MPs (> 1µm) ❖ Non-destructive in nature ❖ Low sample-volume testing	❖ Can be falsified by SOM ❖ Interference with pigments	High	Expensive	1 µm	Sensitive to dark-colored MPs	Limited standardized soil preparation methods	(Guo et al. 2022, Mariano et al. 2021)
Thermal Analysis	**TED-GC-MS**	❖ High sample capacity than Py-GC-MS ❖ No sample pretreatment	❖ Destructive ❖ Cannot identify shape and color	High	Expensive	0.1 µg	High operational cost	Lack of reference materials for soil MPs	(Junhao et al. 2021)
	Py-GC-MS	❖ Characterize and Quantify MPs and other organic additives	❖ Requires sample preparation ❖ Choice of pyrolysis is required	High	Expensive	< 1 µg	Cannot provide shape/morphology	No universal database for soil MPs	(Junhao et al. 2021)

	TGA	❖ Effective for small-volume samples ❖ Fast mass-quantitative detection of MPs	❖ Limited sample capacity ❖ Destructive in nature	High	Expensiv e	10 µg	Limited for small MPs	No consensus on MP degradation parameters	(Huang et al. 2021)
Emerging technologies	**Hyperspectral imaging**	❖ Improved objectivity and rapid bulk analysis	❖ Sensitive to contaminations (hyperspectral peaks may interfere with soil)	High	Expensiv e	>0.5 mm	Soil variations may affect outcomes and require high spectral libraries	-	(Faltynkova et al. 2021, Serranti et al. 2024)

Morphology and Color distribution of MPs in farmland soils

MPs are normally classified in terms of morphology/shape, color and size as they help in identifying the origin of these particles in soils. MPs shapes are generally classified into fragment (sheet, hard angular pieces/ irregular shaped pieces), fiber (line, elongated strings), film (soft transparent flakes/nylons), foam (white and spongy, often spherical), pellets (spherule, ovoid, disc or lentil-shaped) and microbeads (small, solid, manufactured plastic particles).

Fragments and fibers account for most dominant shapes of MPs in numerous studies. For instance, Zhou et al. (2020) and Rede et al. (2025) found dominance of fragments in soils of coastal plain of Hangzhou Bay, China and Viseu, Portugal respectively. Fragments were also dominant in farmland soils of Tainan city (43%), facility and open-field agricultural soils in Shouguang City (46.3%), smallholder farms (60%) and large-scale farms (42%) in China (Fakour et al. 2021, Hao et al. 2023, Yu et al. 2021). MPs fragments are believed to be heavily linked with residual plastic wastes introduced in agricultural production process such as plastic bags, packaging materials and agricultural tools onsite (Kato et al. 2024, Yu et al. 2021).

Fibers are predominant in the study by Liu et al. (2018) (53.33%). Fibers were also dominant in soils applied with sewage sludge in Chile (63%), agricultural soils of Shaanxi Province (49%), farmland soils in Dar es Salaam, Tanzania (49.7%) (Corradini et al. 2019, Ding et al. 2020, Kato et al. 2024). The dominance of fibers has been heavily linked with domestic discharges, sewage sludge application, flooding and irrigation with wastewater (Corradini et al. 2019, Ding et al. 2020, Fakour et al. 2021, Liu et al. 2018).

Film and other shapes like pellets and microbeads are rarely predominant. For instance, films were dominant in the study by Feng et al. (2020) and were associated with mulching film and plastic greenhouses degradation. Pellets are rarely observed in studies they are normally used as exfoliants in personal care products. For instance, Liu et al. (2018) found pellets in farmland soils of Shanghai, China (0.32%) and were only found in shallow soils. Their occurrence in shallow soils remain a limitation in their study calling for further studies. Ding et al. (2020) attested that the presence of pellets in soil without any link to industrial care products could be attributed to diffuse sources to river water or through aeolian transport. The characteristics (morphology, size, type and color) of MPs in farmland soil studies are given in Table 6

.

Table 6: Morphology, size, and color distribution of MPs in farmland studies

Location	Type of resins detected	Morphology	Size (mm)	Color	Reference
Shanghai, China	PP, PE	Fiber, fragment, film and pellet	<1, 1-3, 3-5	black and transparent	(Liu et al. 2018)
Franconia, Germany	PE, PP, PS	Film, fragments, fibers	2-5	White, transparent, blue, green	(Piehl et al. 2018)
Mellipilla, Chile	-	Fiber, film, fragment, pellet	0.16, 2, 4, > 4	-	(Corradini et al. 2019)
Shaanxi Province, China	PS, PE, PP, HDPE, PVC, PET	Fiber, film, fragment, pellets	0-0.49, 0.5-0.99, 1-1.99, 2-5	-	(Ding et al. 2020)
Tibean Plateau, China	PE, PA, PP, PS	Film, fiber, fragment, sphere and foam	<50 µm, 50-100 µm, 100-500 µm, >500 µm	transparent, white, black and others	(Feng et al. 2020)
Hangzhou Bay, China	PE, PP, PES, PA, Rayon, Acrylic	Fragment, fiber and film	1-3	-	(Zhou et al. 2020)
Tainan, Taiwan	PE, LDPE, Oxidized PE, PP, PS	Fragment, fiber, foam, film, pellets, microbeads and others	<1, 1-3, 3-5, >5	Black and white	(Fakour et al. 2021)
Arusha, Tanzania	PP, PS, PET	Fiber, fragment, film and microbeads	2, 1, 0.2, 0.05	-	(Kundu et al. 2021)
Shouguang City, Shandong Province	PE, PP, EPC, PS, others	Fragment, film, fiber, pellet and foam	<0.5 - 5	Transparent, white, green/blue, beige/gray, black, red and others	(Yu et al. 2021)
Taihu Lake, China	PE, PP, PET, PE-PP, PAN, PA, EVA, PVA, PVC, PS	Fragment, fiber, film and particle	<0.3, 0.3-0.6, 0.6-1, 1-3,3-5 > 5	Black, white, transparent, blue, green, red, others	(Hao et al. 2023)
Dar es Salaam, Tanzania	PE, PP, PET, PS,	Fiber, fragment and film	-	White, blue, brown, black and red	(Kato et al. 2024)
Viseu, Portugal	PE, PP	Fragment and fiber	-	-	(Rede et al. 2025)

Environmental and human health risks of MPs in Soils

Microplastics pose a long-term direct or indirect effect on soil quality, plants and animals including humans who are inevitably at higher risk due to transfer of these pollutants via food chain (Kumar et al. 2020). The risks of soil MPs were put forward by Rillig in 2012 when he attested that microplastics could have severe adverse effects on soil functioning, biodiversity and soil properties. Ever since scientists have been conducting research in-depth about these widespread contaminants and their environmental and health implications. In this section we will dive into health risks associated with soil MPs from soil quality, soil organisms, plants and their movement in the food chain.

Soil quality

Once MPs gain entry into soils, the van der Waals forces and isoelectric coagulation coulomb force become altered. MPs can alter fundamental physical and chemical properties of soil including density, structure, water infiltration rate and the ability to capture essential nutrients (Guo et al. 2022). de Souza Machado et al. (2019) found that physical parameters such as evapotranspiration increased by 35% by polyamide (PA) and 50% by polyester (PES). Moreover, soil bulk density decreased by the presence of polyethylene high density (PEHD), PES, PP and PS. PE fibers increased water-holding capacity however, they significantly reduced bulk density. The results imply that different MPs can result in different effects on the soil's basic properties (de Souza Machado et al. 2019, Ding et al. 2022). Microplastics depending on their sizes can block pore spaces preventing air and water entry which relatively affects soil quality. MPs can also modify chemical properties such as organic phosphorus, organic nitrogen, ammonium nitrogen and phosphate, which in turn impact soil nutrients putting significant pressure on plant growth and soil fauna (Campanale et al. 2022). Furthermore, MPs themselves in their nature are usually added with additives including flame retardants, plasticizers and stabilizers during the manufacturing and processing processes (Kumar et al. 2020). These additives become progressively released into soils after prolonged exposure to the environment resulting in negative effects on soil functioning and microbial diversity (Yu et al. 2022).

Soil organisms

Microbial activity is crucial for the decay of SOM and nutrient cycling necessary for root development and plant growth. The buildup of microplastics in soils may have resulted in direct and indirect effects on microbial populations including soil fauna (Okeke et al. 2023). Because of their relatively small size, accidental ingestion of MPs can result in mechanical damage to the esophagus of soil creatures, intestinal obstruction, decreased fecundity and biochemical responses such as lowered immune responses and metabolic disturbance (Pérez-Reverón et al. 2022). Consequently, MPs may induce soil animals to experience false satiety which may lower their carbon biomass intake and increase their energy consumption ultimately leading to slower growth or even death (Wang et al. 2022). Evidence has shown that earthworms and springtails may be hampered in their ability to freely move within the soil due to microplastic adherence in their outer surfaces (Pérez-Reverón et al. 2022). It is through soil organisms MPs transfer via the food chain due to the feeding mode (Ding et al. 2022). Studies have confirmed that earthworms ingest microplastics and succumb to effects including gut damage, growth inhibition, weight decrease, reproduction issues and immune response (Ding et al. 2022, He et al. 2018, Huerta Lwanga et al. 2016).

Plants

Soil MPs have an impact on the growth of plants including edible species, raising questions about food security (Campanale et al. 2022, de Souza Machado et al. 2019). MPs find their way into plant tissues due to their particle sizes, morphology and chemical composition. The smaller the size, the greater the toxicity to plants (Okeke et al. 2023). During transfer into plant tissues, they behave as nanomaterials. Their absorption occurs in apoplastic and symplastic ways through the root system (Campanale et al. 2022). Apoplastic transport follows the extracellular spaces and cell walls and continues in a symplastic way by crossing the Casparian strip. Symplastic involves passage through the membrane of radical cells and plasmodesms. Guo et al. (2022) attested that MPs can affect plants directly via roots or indirectly through altering the physical and chemical properties of the soil. MPs have a large surface area for adsorbing a plethora of chemical cocktails. These pollutants may find their way into the plant cells and cause far more damage up the food chain (Campanale et al. 2022). Iqbal et al. (2023) provided a further effect of microplastics on crop seed germination, growth, metabolic processes, tissue and root development by attesting that MPs can cause cytotoxic and genotoxic effects on roots of crops. Figure 3 describes the environmental implications of soil MPs.

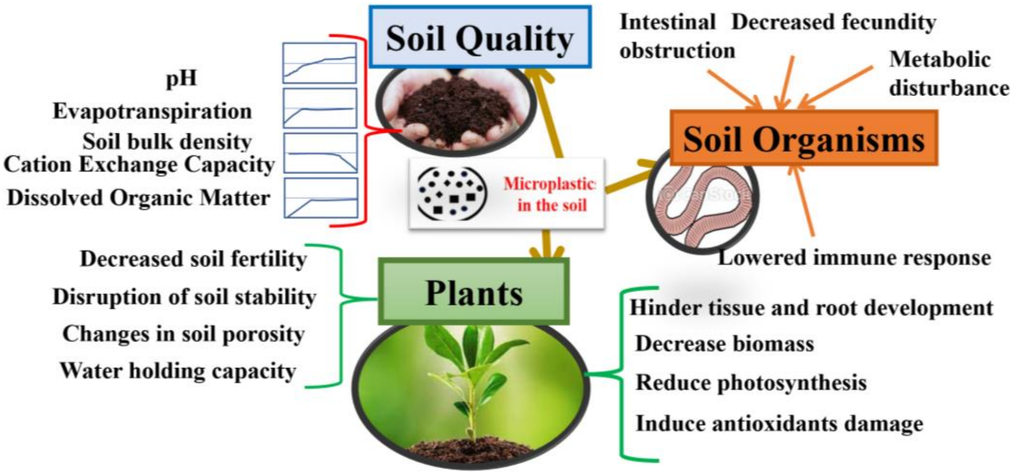

Figure 3: Environmental implications of soil MPs adopted from Guo et al. (2020) and Pérez-Reverón et al. (2022)

Human Health Risks of MPs

Evidence linking the effects of MPs and human health is still limited. However, a potential threat exists once MPs degrade or fragment in soils, they may be absorbed and enriched by plants, transported or ingested during microbial activities and then transferred and accumulate along the food chain (Kumar et al. 2020, Okeke et al. 2023, Perković et al. 2022, Zhang et al. 2022). MPs can be absorbed especially by vegetable roots and further to edible parts of the plant and cause adverse effects (Zhang et al. 2022). These effects tend to differ according to their sizes and point of target for example, Li et al. (2020) discovered that microplastics with sizes 0.2 and 2 µm can penetrate through the roots of lettuce and wheat and enter the leaves. Nanoplastics have been mostly found in fruits, crops and vegetables with the highest concentrations detected in apples and carrots (Perković et al. 2022). These studies imply that MPs may enter either seeds/fruits of crops and the human body through food intake.

Risks of MPs to human health also arise due to the release of additives that are known to be endocrine disruptors or carcinogenic such as phthalates (Pathan et al. 2020). Moreover, due to their large surface area, MPs can adsorb contaminants from the environment such as heavy metals, and persistent organic pollutants with the potential to enhance their transfer and uptake along the food chain (Perković et al. 2022). Once they enter together with MPs, they end up causing endocrine disorders, diabetes, obesity and cancer (Perković et al. 2022). Studies have also highlighted the presence of MPs in the human intestine (Fackelmann and Sommer 2019), adult stool (Schwabl et al. 2019) and colectomy specimens (Ibrahim et al. 2021). Gastrointestinal problems such as local inflammation and destruction of microbial composition and MPs penetrating the intestinal barrier and entering the circulatory system are associated with MPs in the digestive tract (Fackelmann and Sommer 2019, Teles et al. 2020, Yu et al. 2022). Studies have also found trophic transfer of MPs for instance, Huerta Lwanga et al. (2017), first found that microplastics and macroplastics in home gardens can transfer from soil to chickens, with a relatively high concentration of 129.8 ± 82.3 particles g^{-1} in chicken feces. This implies MPs can transfer via trophic pathways and potentially into humans.

Apart from food consumption and trophic transfer, studies have also revealed that microplastics can enter the human body through inhalation with particle sizes similar to $PM_{2.5}$ and enter the bloodstream triggering immune reactions, respiratory tract irritation and asthma (Jung et al. 2022, Yu et al. 2022). Dermal contact has been regarded as a less significant exposure route, however, it has been put forward that particles with less than 100 nm could cut across the skin barrier rendering farmers who are closely in contact with soils at greater risks (Prata et al. 2020). MPs toxicity is linked with exposure concentrations, individual susceptibility, particle properties, adsorbed contaminants and tissue involved / target organ and data is still scarce (Prata et al. 2020). Effects of MPs in the human body are not specific for MPs from agricultural soils (Perković et al. 2022). It is still impossible to estimate human exposure to MPs through food intake due to the scarcity of validated methods and the lack of standardized analytical methods used for reporting (Toussaint et al. 2019). Research on MPs inhalation and dermal route is still minimal (Blackburn and Green 2022, Domenech and Marcos 2021). Further research is needed to link human health with MPs intake through soil food web including rigorous clinical studies. Figure 4 highlights the effects of MPs on human health.

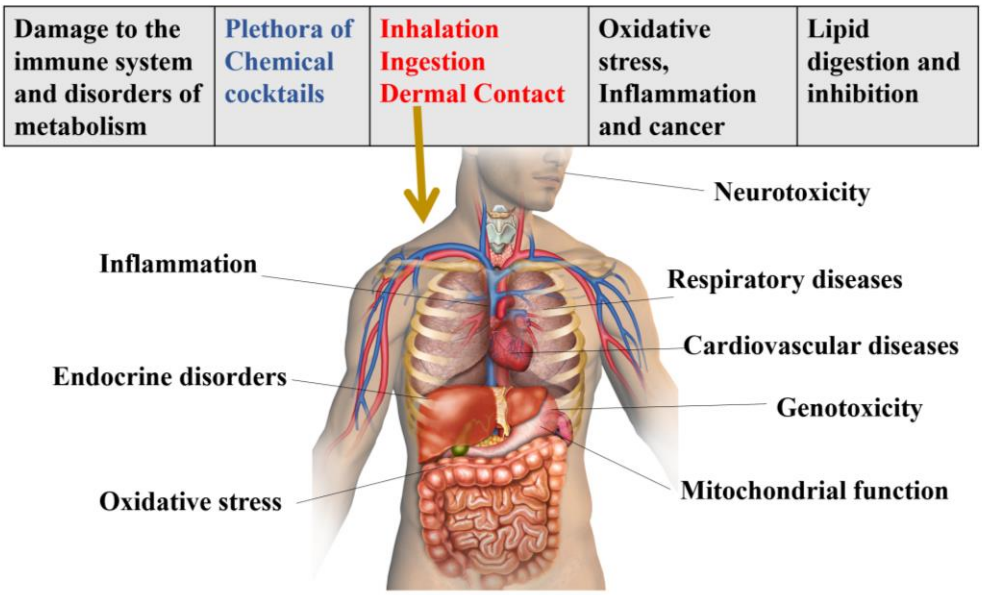

Figure 4: Human Health implications of soil MPs with modifications from Perković et al. (2022) and Yu et al. (2022)

Conclusion

MPs in agroecosystems is directly linked with the Anthropocene era and is set to increase amidst increasing plastic production. Joint efforts are needed between government, non-governmental organizations, stakeholders, consumers and manufacturers to address plastic pollution by redesigning products in an eco-friendly manner including effective legislation, circular economy and life cycle assessment initiatives to address the challenge of MP pollution. This review summarized sources, types, analytical methods, environmental and human health risks of microplastics in farmland soils. Soil MPs come from wide range of sources primary or secondary and are unevenly distributed. Numerous methods have been developed to identify and characterize MPs. Density separation, combined with H_2O_2 digestion, Fenton's reagent and visual or spectral identification is the most common and relatively cost-effective method. Although different methods have been developed, yet a standardized method for detection of soil MPs that follows green chemistry principles is imperative. Although studies are limited, soil MPs are linked to cause detrimental effects to human health. However, there is a potential pathway of MPs to seep into soils and enter in plants even in the edible parts and further enrich and accumulate along the food chain.

Future research directions and perspectives

The current trend and status of the soil are worsening due to the buildup of MPs, their adsorbed chemical cocktails and the environmental and health implications they pose to the environment. Therefore, urgent attention is needed to restore farmlands and save food systems. Some loopholes and challenges must be addressed and justified with more efforts to tackle agricultural plastics pollution. These include:

- A need for establishing standardized protocols for identifying and quantifying MPs in farmland soils from sampling, separation, digestion and detection of soil MPs to enhance effective comparison and upscale effective monitoring plans. Moreover, develop a reliable methodology that follows green chemistry principles.
- Determine optimum temperature and time conditions for H_2O_2 digestion in order to reduce risk of MPs fragmentation
- Validate and assess oil extraction methods under different soil type and conditions and additional clean up mechanisms to improve its efficiency.
- Fate and behavior of microplastics along the soil profile including their characteristics of occurrence
- Further studies linking human health with soil MPs, their entry pathways including inhalation, ingestion and dermal contact, trophic transfer, toxicity and human health risk assessment
- Further studies on MPs toxicity in humans under different particle properties, exposure concentrations
- Further studies to examine the additive effects of the combination of these plastics and the adsorbed chemical cocktails on the soil and terrestrial environment.

Abbreviations

ABS	Acrylonitrile Butadiene Styrene
DS	Density separation
DW	Dry weight
EVA	Ethylene Vinyl Acetate
FTIR	Fourier Transform Infrared
HDPE	High-density Polyethylene
LDPE	Low-Density Polyethylene
MPs	Microplastics
OE	Oil extraction
OECD	Organization for Economic Co-operation and Development
PA	Polyamide
PAN	Polyacrylonitrile
PC	Polycarbonate
PE	Polyethylene
PEHD	Polyethylene high density
PES	Polyester
PET	Polyethylene Terephthalate

PP	Polypropylene
PS	Polystyrene
PVC	Polyvinyl chloride
Py-GC-MS	Pyrolysis Gas chromatography-mass spectrometry
SEM	Scanning Electron Microscope
SOM	Soil Organic Matter
TED-GC-MS	Thermal extraction desorption gas chromatography-mass spectrometry
TGA	Thermal gravimetric analysis

Declaration of Competing Interest

The authors declare that they have no known competing interests, financial or non-financial, that could potentially influence the integrity or objectivity of this research.

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