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REVIEW ARTICLE

MICROPLASTICS IN AGRICULTURAL SOILS: EMERGING THREATS TO CROP SAFETY AND FOOD SECURITY

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ABSTRACT

Microplastic (MP) contamination has become a great environmental threat, classically considered as exclusive to aquatic systems; yet, evidence suggests that agricultural soils currently act as important sinks of MPs. Widespread use of plastic materials in agriculture (e.g., mulching films, greenhouse covers, sewage sludge amendments, compost application and contaminated irrigation water) has expedited the enrichment of microplastics on terrestrial ecosystems. This newly emerging pollution posed great risks to soil health, crop production and food safety even world food security. Microplastics in soil have negative effects on the physical structure of soil like porosity formation and aggregation, the size and composition of microbial community in soils which are more environmental functional traits as well as with key functional biogeochemical cycles. Furthermore, microplastics may adsorb and transport co-contaminants, such as heavy metals and pesticides, enhancing their ecological toxicity. Emerging studies also show the absorption and transportation of microplastic particles in crop plants, thereupon entry into food chains and potential human consumption are some concerns. However, our knowledge is however still limited about the fate and long-term impact of microplastics in soil–plant systems, as well as their transport processes within that environment. The absence of standardized detection methodologies, toxicological endpoints, and field-based measures continues to limit the ability to conduct reliable risk assessment. This review provides an overview on sources behavior, interactions with soil–microbes, pathways for crop uptake and analytical methods of detecting microplastics in agricultural soils. Finally, some critical research gaps and the future perspectives are summarized to facilitate sustainable agricultural strategies used for protecting food security against increased microplastic pollution.

KEYWORDS

Microplastic, Agricultural soil, Crop uptake, Soil pollution, Food safety

1. INTRODUCTION

With an exponential increase in plastic manufacturing and consumerism over the past few decades, plastic debris has caused significant global environmental pollution. Although marine ecosystems are more studied in the context of plastic pollution, terrestrial environments (i.e., agricultural soils) have recently been acknowledged as one of the major, although understudied, microplastics sink (Tian et al., 2022). Microplastics, which are commonly referred to as fragments smaller than 5 mm of plastic items or in the form of micro-sized materials, generally enter the environment from larger plastic products. At the agricultural level, a variety of human activities can contribute to pollution with these compounds, including use of plastic mulch films and drip irrigation pipes, greenhouse coverings, application of sewage sludge or composts as amendments and crop irrigation with surface waters at polluted sites or with wastewater from municipal treatment plants (Jia et al., 2022). Thus, agricultural soils are coming into contact more often with the long-lasting, persistent plastic residues that may remain in this environment for a long time. The occurrence of microplastics in soil introduces new concerns for soil quality and ecosystem health. Soil is a highly complex and dynamic medium that favours the habitat of microorganisms, nutrient cycling, water flow, and root growth (Wu et al., 2024). The presence of external plastic pollutants changes soil properties such as bulk density, porosity and aggregate stability. Microplastics can also function as new ecological niches for microbial colonization, and hence may alter soil microflora community composition and activities (Deng et al., 2024). Alterations in microbial community structure and enzymatic activities can ultimately affect nutrient availability and crop productivity. Aside from their effects on soil health, the hazards of microplastics may extend to crop safety. Recent experimental studies suggested that some microplastics could be ingested by plant roots into aerial tissue (Kumar et al., 2020). It represents a new route of exposure to microplastics in the human food web. Secondly, microplastics exhibit an outstanding adsorption capacity to toxic pollutants, such as heavy metal, persistent organic contaminants (POC), and pesticide residues; thus they behave like a vector of secondary pollutants in the soil plant system. These interactions may enhance ecological toxicity and add to food safety concerns (Kedzierski et al., 2023). However, knowledge gaps still exist in the field of microplastics in agricultural soils. Long-term field monitoring is limited, standardized methods for sampling and detection are emerging, and the threshold concentration causing ecological or crop harm is poorly constrained. Therefore, an integrative review of the literature is required as a means to understand the scope of the issue and provide direction for future research (Mahmud et al., 2025). The presented review summarizes the

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existing knowledge regarding origins, fate, soil–microbe interactions, crop uptake pathways and detection techniques of microplastics in agroecosystems with emphasis on identifying important research gaps for sustainable crop production and global food safety (Zhang et al., 2020).

2. POTENTIAL SOURCES FOR MICROPLASTICS IN AGRICULTURAL SOILS

The sources of microplastics in agricultural soils are both diverse and associated with anthropogenic inputs, emanating from modern farming and waste processing practices. Among the major contributors is the pervasive use of plastic mulching films, which are popularly used for enhancing soil temperature, moisture conservation and weed control (Ren et al., 2024). Over time, these thin films break down under the influence of UV radiation as well as mechanical stress during tillage and then become fragmented into smaller plastic particles that remain in soil. In several areas the partial absence of mulching residue removal in post-harvesting stages even increases the rate of microplastics accumulation and causes long-term soil pollution (Fakour et al., 2021). The application of sewage sludge and organic compost to the soil is another important route for the entry of microplastics into agricultural land. Wastewater treatment plants are also recognized reservoirs for large amounts of household- and industrial-derived microplastics. There are many embedded microplastic particles in the sludge after treatment and when spreading this treated sludge on farmland, those particles can be easily transferred from the biosolid to soil systems during fertilization (Huang et al., 2020). Likewise composted product from municipal solid waste can have lumps of plastic in it if the separation scheme was not performed well. It can cause microplastic content to slowly rise in agricultural soils due to multiple applications of these amendments. Irrigation is another factor in adding to microplastic pollution, especially where surface water, groundwater or treated wastewater are utilized for irrigation of crops (Kim et al., 2021). Microplastic particles in water bodies can be flushed to the soil when used for irrigation and further incorporated into the soil frame. Also, irrigation infrastructure made of plastics like drip lines and storage tanks, can suffer from environmental stress resulting in plastic particles being released directly into farm fields (Zhou et al., 2023). Atmospheric deposition is another neglected but emerging contributor to microplastics in terrestrial environments. It has been shown that microplastic fibers and particles can be spread by air currents, and transferred to soil through rainfall or dry deposition. This process can spread microplastic pollution even in farmland that is away from direct plastic use or urban waste sources. Finally, some agricultural inputs such as coated fertilizers, controlled-release nutrient formulations and pesticide packaging could represent additional minor-sources of plastic residues in soils (Harms et al., 2021). The growing use of polymer-coated fertilizers for increased nutrient use efficiency injects synthetic polymers which may degrade to microplastics, following nutrient release. Together, these various input routes demonstrate that the microplastic pollution in agricultural soils does not have a single origin but results from interlaced agricultural and waste management processes. By integrating these various origins, we can not only explore the effects but also propose some intervention measures for reducing microplastics entering soil–crop systems (Guo et al., 2023).

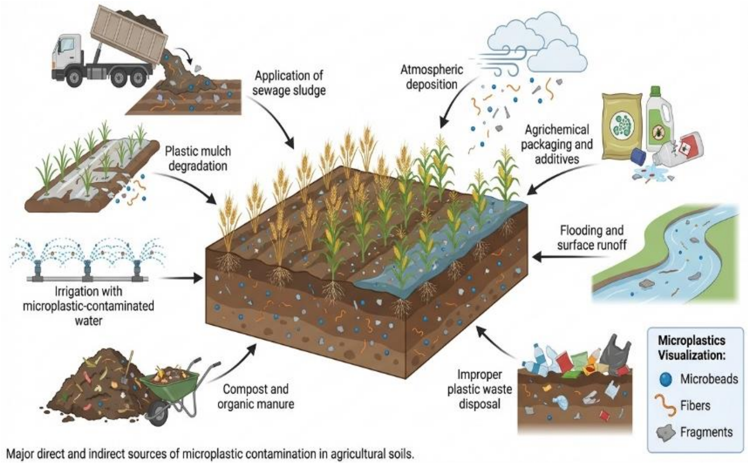

Figure 1: Showing potential sources of microplastic in agricultural soil

Table 1: Major sources of microplastic in agricultural soil and their contribution level

Sources	Description	Contribution to soil microplastic	Reference.
Plastic mulching	Agricultural film	High	(Lwanga et al., 2022)
Sewage sludge	Fertilizer amendment	Medium	(Chen et al., 2022)
Compost	Municipal organic waste	Low-medium	
Irrigation water	Reclaimed water	Medium	
Atmospheric deposition	Wind/rain deposition	Low	

2.1 Destiny and behavior of microplastics in agricultural soil

After being released into farmlands, microplastics undergo complicated physical, chemical and biological processes which ultimately dictate their fate, transport and eco-toxicological effects. Because they are synthetics and hence have a polymeric structure, the majority of microplastics are also not very biodegradable, thus remaining in soil for long periods (Yibo et al., 2024). Environmental forces such as UV, temperature differences and mechanical damage will slowly break down bigger bits of plastic into smaller micro- and nano-plastics with higher surface to volume ratios and thus more reactive. This ongoing degradation is speculated to lead to an overall increase in concentrations of microplastic particles over time in farmed soils. The fate and behavior of microplastics in soil depends on their physicochemical properties such as size, shape, density, and nature of the polymer. Softer, less dense plastics (e.g., polyethylene and polypropylene) are often found to be retained close to the soil surface while denser polymers have been reported to move situationally further into the soil mass via leaching and bioturbation (Belioka et al., 2024). Soil structure, OM content, and soil moisture status also control the vertical and lateral movement of microplastics within the soil body. Earthworm activity as well as root growth could also mediate the transport of these microplastics deeper down in soil, which would make the possibility to come into contact with plant roots higher. Microplastics easily associate with soil particles and organic matter to form aggregates, which could change the structure of soils and water-holding capacity (Sandil et al., 2024). The surfaces of the biochar have capacity to adsorb a variety of organic and inorganic contaminants such as pesticides, polycyclic aromatic hydrocarbons and heavy metals. This adsorption process turns microplastics as mobile carriers of co-contaminants, which may increase bioavailability and toxicity of these pollutants in soil–plant systems. Moreover microplastics may form biofilm on their surface creating new environments for colonization of microbial species (Bello et al., 2025). If you have a 'plastisphere' and it has its own independent community of

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other organisms that are stratified to concentrate on the polymers that make up plastics, those communities may be profoundly different from the naturally occurring soil microbiotas," said Grime. "That could potentially change what is happening in terms of how microorganisms interact with each other, or nutrient cycling (Leonard et al., 2024)." With aging, oxidation and surface cracking of microplastics would result in a change of the chemical properties, particularly their reaction with soil minerals and biological factors over time. These changes shall augment the adsorption capacity of pollutants with microplastics and boost their potential internalization by plant roots. While research on this subject is increasing, the ultimate destiny of microplastics in a real field environment over the long-term period still lacks understanding (Athulya et al., 2024). Data are scarce on the rates of degradation, residence times, and threshold concentrations at which they cause detrimental effects on soil or crop. Hence, the investigation of environmental fate and behavior of MP in agricultural soil is indispensible to estimate its long-term potential ecological risk and design Strategies to mitigate them (Hassan et al., 2025).

2.2 Microplastics–Soil–Microbe Interactions

Soil microbes are of critical importance in the regulation of soil fertility, nutrient cycling and plant growth. Input of microplastics to agricultural soils can be considered a new environmental pressure that may affect soil microbial community composition, diversity and functional potential. From the other point of view, as they are persistent and chemically stable, microplastics represent new surfaces for microbial colonization resulting in unique community compositions of biofilms; this particular kind of community has been defined as "plastisphere" (Wang et al., 2022). Such plastisphere-associated microbes could be markedly different from those in native soil microbial communities, and thus change microbe-microbe interactions, affecting important soil biochemical cycles. Microplastics can alter soil physical properties, e.g., porosity and aeration, and water-holding capacity as well as regulate microbial habitats and metabolic activity indirectly (Sun et al., 2022). Changes in soil structure could be able to modify O2 diffusion and moisture availability, thereby affecting microbial respiration rates, as well as enzymatic activity. Microbial biomass composition and community profiles have been observed to shift in several experimental studies owing, for example, to particular bacterial and fungal taxa increasing or decreasing when exposed to microplastics. These imbalances can interfere with key nutrient processes like carbon mineralization, nitrogen transformation, and phosphorus solubilization contributing to eventual changes in soil fertility and crop nutrient supply (Shi et al., 2022). Aside from the physical effect, microplastics can impose chemical stress to the soil microbes of plastic additives released from it including phthalates, bisphenols, and flame retardants. These substances can be toxic, by preventing microbial growth and enzymatic activity. In addition, microplastics absorb pesticides, antibiotics and heavy metals easily and accumulate the contaminants on their surface. Once colonized by microorganisms, these pollutant-laden MPs could create a localized toxic effect, thus applying selective pressure to microbial communities and possibly encouraging the spread of resistant or pathogenic strains (Aralappanavar et al., 2024). The interaction between microplastics and soil microbes could also impact plant–microbe symbionts, such as mycorrhizae and plant growth-promoting rhizobacteria. Modification of these mutualistic relationships can affect plant nutritional acquisition efficiency and tolerance to abiotic and biotic stress. On the other hand, some microorganisms have exhibited slight potency of colonization and degradation to several kinds of BD- plastics, representing potential acclimatization at soil level (Shi et al., 2023). However, the ecological value and efficiency of this degradation in the field are still not well understood. Although interactions between microplastic and microbes are increasingly being recognized the current knowledge, however, has mainly been derived from short term laboratory experiments with artificially high microplastic concentrations. To date there is a general lack of long-term field-based studies, thus restricting the ability to accurately assess ecological risks. Thus, getting to know detailed mechanisms which microplastics reshape the soil microbial connections and functions is very important for predicting its ecosystem-wide implications of soil health, crop productivity and sustainable agriculture systems (Helmberger et al., 2020).

2.3 Uptake of Microplastics by Crops

In particular, the possible accumulation and mobilization of microplastics in crop plants has received considerable recent attention given its immediate relevance to food safety and human health. As a common belief, plastic particles are large and cannot enter the plants; but recent evidences suggest some types of micro-and nano-plastics can penetrate to plant root systems under certain conditions (Li et al., 2020). Root uptake is affected by several factors such as particle size, surface charge, polymer composition and the physicochemical properties of soil on which they are released. It is particularly expected that smaller microplastics and nano-plastics would more readily infiltrate root epidermal barriers through intercellular spaces, cracks during the emergence of lateral roots, or endocytosis-like processes to enter internal plant tissues (Liu et al., 2022). Microplastic particles, once inside roots, can be translocated into stems and leaves through the vasculature and even in certain cases to edible tissues such as grains, fruits, or vegetables. Experiments on wheat, lettuce, rice and cucumber demonstrated the presence of microplastic particles in aboveground plant tissues and have confirmed their translocation potential. While the degree of efficiency of transport differs between plant species and particle types, these data identify a hitherto neglected exposure pathway through the food chain (Tang et al., 2022). The occurrence of microplastics in human-consumable plant tissues raises important matters about food safety, nutritional value and potential long-term health consequences to consumers. In addition to physical build-up, microplastics can also disrupt root physiological activities. They can cause oxidative stress, damage on cell membrane and changes of nutrient and water uptakes once inside roots (Li et al., 2020). Several reports have indicated that shortening of roots, loss of photosynthetic capacity at different plant organs are observed in various crops following microplastic exposure which may lead to the possible reduction on crop growth and yield. Furthermore, microplastics laden with the adsorbed pollutants (i.e., pesticides and heavy metals) may serve as a vector to transport the secondary toxic compounds into plant tissues, which increase the phytotoxic effects. Notwithstanding these alarming observations, information on microplastic uptake in realistic field situations is lacking (Roy et al., 2024). The majority of the available studies have been made under artificial laboratory or hydroponic conditions at relatively high microplastic concentrations, and these conditions do not necessarily reflect those that microplastics experience in agricultural soil. In addition, it is technically difficult to identify microplastics in plant tissues; standardized sampling, extraction and identification methods are not yet available. Further studies are urgently warranted to quantify and characterize the microplastic exposure in field-cultivated plants, establish exposure threshold doses and address long-term implications on food safety and humans (Ebere et al., 2019).

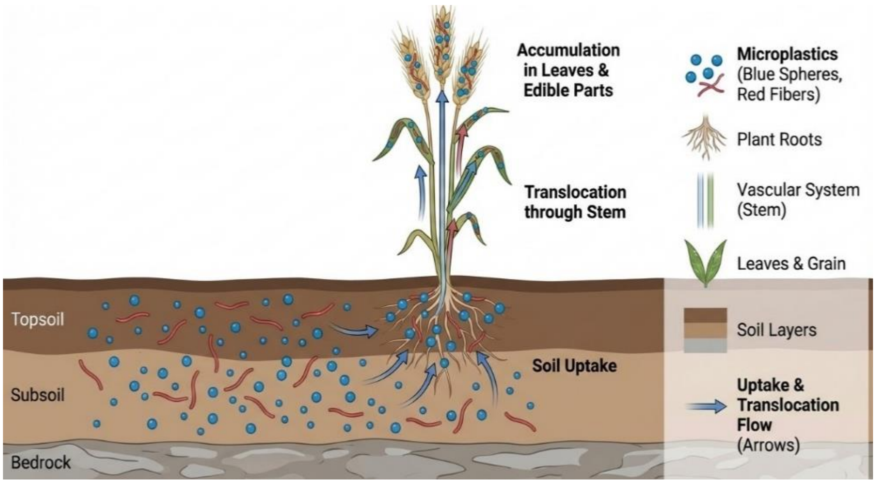

Figure 2: Uptake and translocation of microplastic in field crops

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Table 2: Summery of microplastic uptake, translocation and growth effect in major crops species

Crops	Microplastic size	Uptake observed	Translocation	Effect of growth	Reference
Wheat	PE 5 µm	Yes	Root- shoot	Reduced biomass	(Jadhav et al., 2024)
Lettuce	Ps 1-10 µm	Yes	Leaf accumulation	Oxidative stress	(Jia et al., 2023)
Rice	PE/PP fragments	Yes	Grain detected	No significant	
Cucumber	PE nanoparticles	Yes	Leaves	Reduce root elongation	

3. MICROPLASTIC AS A VECTOR OF CO-POLLUTANTS IN SOIL–CROP SYSTEMS

Microplastics have high-surface features that make them capable of adsorbing various organic and inorganic pollutants, which result in their being potentially mobile carriers for secondary contaminants in agricultural fields. Microplastic particles are easily adsorbed by pesticides, herbicides, antibiotics, polycyclic aromatic hydrocarbons and heavy metals in the soil owing to their large surface to volume ratio and hydrophobicity as well as their high chemical stability (Tziourrou et al., 2025). This adsorptive potential can enable microplastics to accumulate contaminants from the overlying environment (and at levels greater than bulk soil). It is therefore that microplastics play a role of physical contaminant as well as carrier to help the transportation and redistribution of toxic compounds among soil plant systems (Shaji et al., 2025). Once pollutant-rich MPs are introduced to arable soils, they can change the fate and bioavailability of co-existing pollutants. Chained pollutants could be then slowly released under soil reactivity changes (pH, temperature or microorganisms), implying continuous risks of chronic exposure for soil microorganisms and plant roots (Mo et al., 2026). This long-term release may prolong the effects of agrochemicals or toxic metals after their application windows, which in turn can have consequences for soil microbial processes and nutrient cycling. Furthermore, microplastics may be transported through soil profiles which facilitates the transfer of sorbed pollutants throughout deeper soils or aquifer systems (Kumar et al., 2025). The carrier role of microplastics also is important for crop contamination. When the adsorbed pollutants carried by the MP particles are taken up into plant roots, they can directly transport secondary toxic compounds into plants. This could lead to higher phytotoxicity and also high potential of contaminant accumulation into wholesome parts of the plant. Studies have shown that microplastics can increase the adsorption uptake of heavy metals, e.g., Cd and Pb, by crops through experimental methods, which may pose extra threats to food safety and human health (Tariq et al., 2025). Likewise, adsorption of pesticide degradation products on microplastics can change their degradation behaviours and lead to unexpected avenues for exposure. In addition, microplastics could affect the environmental fate of contaminants due to creation of additional reaction surfaces for chemical modifications or a substrate adhered by microbial populations. Biofilms on the surface of microplastics be a home for microbes with the capacity to transform adsorbed pollutants, and produce more toxic or durable intermediaries. Such multilevel interactions along with microplastics, co-pollutants, soil microbial community and plants bring new problems into predicting the fate of the contaminants in agricultural systems (Athulya et al., 2024). Despite the increasing recognition of microplastics as vectors of pollutants, quantitative knowledge of adsorption mechanisms, and release kinetics is scant both in isolation and interactions to toxicity under realistic field conditions. It is recommended to focus on the interactive effects between microplastics and agrochemicals in further studies to accurately evaluate cumulative ecological risks, so as to provide guidance for reducing risk in soil management and crop production (Mahmud et al., 2025).

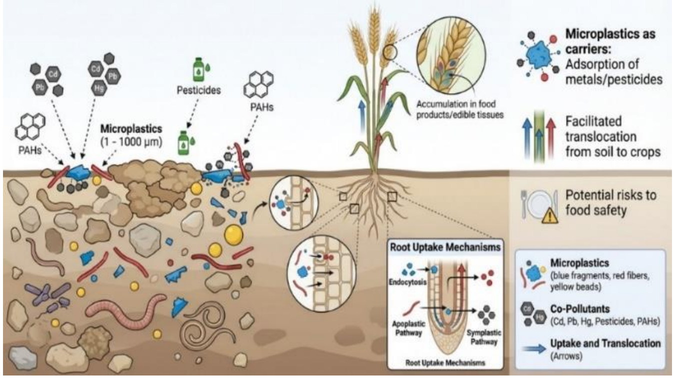

Figure 3: Microplastic as vectors of co-pollution in agricultural soil: adsorption, transport, and crop uptake pathway

Table 3: Microplastic as vectors of co-pollution in soil-crops system: Types, sources and impact

Pollutant types	Sources	Adsorption on microplastic	Potential crop impact	Reference
Heavy metals (Cd, Pb, Zn)	Soil contamination, fertilizers	High	Root uptake → reduced growth, grain contamination	(Chen et al., 2025)
Pesticides (glyphosate, chlorpyrifos)	Agrochemical application	Medium-high	Translocation to edible tissues, phytotoxicity	(Garbisu et al., 2025)
Organic pollutants (PAHs, BPA)	Sewage sludge, irrigation water	High	Oxidative stress in plants, bioaccumulation	
Antibiotics	Sludge, wastewater irrigation	Medium	Microbial community shift, indirect crop effect	

3.1 Methods and Techniques of Microplastic Detection and Analysis in Soil and Crops

The precise identification and quantification of microplastics (MPs) in agricultural soils and crops are critical to evaluate their contamination levels as well as ecological risks. Nevertheless, detection of microplastics in complex matrices such as soil and biota is technically still challenging by the particle heterogeneity, small size and OM interference (Sang et al., 2016). There are there phases in typical analytical methods, including sampling and pretreatment, extraction and separation, spectroscopic detection. Soil and plant samples are then dried, sieved and treated with oxidizing agents (e.g., hydrogen peroxide) or enzyme to extract the organic fraction without affecting the plastic particles (Pérez et al., 2022). Microplastics are typically separated from heavier soil material with density separation in saturated salt solutions, using for example sodium chloride or zinc chloride. Filtration methods also concentrate isolated particles on to membranes for additional investigation. Polymer identification is routinely carried out by spectroscopic techniques. The characterization of the type of polymer of microplastics based on their molecular vibrational signature is mostly performed using Fourier Transform Infrared Spectroscopy (FTIR) and Raman spectroscopy (Erdem et al., 2023). With micro-FTIR imaging, particles of size down to 10–20 µm can be effectively detected; however, analytical spot sizes for Raman spectroscopy can provide even higher spatial resolution in order to detect sub-micrometer and particularly nano-particulates. Thermal analytical methods, such as pyrolysis GC–MS, are also used to quantify polymer composition by detecting thermal products. In plant material, further digestions are necessary to dissolve cellulose and lignin before extracting microplastics. Nevertheless, as there is not yet a standardized protocol for the extraction and detection of plant microplastics, reported data in this field are heterogeneous. Furthermore, the identification of synthetic microplastics and differentiation from natural fibers remains an ongoing challenge (Cusworth et al., 2024). Notwithstanding many recent technological developments, existing detection procedures tend to be very time-consuming, costly and frequently do not enjoy protocol harmonization. Lack of standardized sampling, extraction efficiency controls and units of reporting prevents comparability between studies. To this end, cost-effective and standardized analytical methods that are also fast are necessary for extensive agricultural microplastic monitoring (Ai et al., 2023).

3.2 Unresolved Issues and Further Research

Although microplastic contamination in agricultural soils is under intensive investigation, there are still many unanswered questions. The absence of long-term field-based studies is one of the major constraints. The majority of studies have been carried out in the lab, with artificially high concentrations of microplastic, which may not be representative for these agricultural environments. Therefore, the real levels of exposure and accumulation as well as long-term field effects are largely unknown. A further huge gap is the very poor amount of knowledge on nano-plastics in soil–plant systems. Although much less studied, nano-plastics are expected to be more biologically active and permeable in plant and microbial cells than microplastics. Yet, detection of nano-plastics is still insufficient to accurately estimate their environmental occurrence and biological effects. Interference problems have been further hampering the development of this research field. At present there are no established standard procedures for sampling, extraction, identification and quantification of microplastic from soil and plant organs (Chen et al., 2025). There is thus an absence of harmonization which hampers comparisons when integrating data between studies in risk assessment. Furthermore, threshold levels for soil toxicity, crop injury and food safety risk are unclear. Interplays between microplastics and other environmental stressors are another interesting but less explored field. Synergistic impact Interaction of microplastics along with climate stress, soil salinity, droughts, pesticides and heavy metal; this combined effect might increase synergestic impact on soil health et al., 2025) (Chandel. The consideration of these interactive effects is important in the context of a realistic ecological risk assessment. From the perspectives of mitigation, we know little about what works in practical terms to reduce inputs of microplastic into agricultural soils. Scientific guidance is still needed in the areas of development of biodegradable mulching materials, and improvement of waste management practices as well as policy regulations for sludge and compost application. In the future, long-term monitoring field studies and standard of methods are also requested to focus on nano-plastics in the environment and the development of advanced detection instruments and risk assessment approaches. Soil science, plant physiology, microbiology and environmental chemistry need to be combined in order to address the potential sustainable practices that can reduce microplastics pollution of agroecosystems (Sana et al., 2020).

4. CONCLUSION

Microplastic pollution on agricultural soils is now recognized as a serious environmental, soil health and food security issue. Many agricultural practices and disposal of waste bring about the constant introduction of microplastics into soil systems, where they remain, interact with soil compounds, change microbial activities and move other co-contaminants. Increasing detections from crops also increase concern about possible food safety risk and related human exposure routes. That the long-term field performance, thresholds for toxicity and standardized detection methods of such chemicals are not known with certainty despite growing scientific interest. Filling these knowledge gaps through interdisciplinary research and by enhancing monitoring methodologies is crucial to allow for accurate risk assessment. Sustainable agricultural approaches and biodegradable eco-friendly alternatives of common plastics, along with science-based policy solutions will likely be effective in addressing microplastic pollution. For this reason, proper knowledge of microplastic fate in soil–crop systems was of utmost importance to protect environmental sustainability and global food security for future decades.

Author contributions

SKB: Conceptualization, Data curation, Writing, Investigation, Methodology; MNM: Super-vision, Validation, Writing-original draft, review and editing; SMET: Data curation, reviewing, visualization; ZZN: Reviewing, conceptualization, Data curation.

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Data availability

All the data are available in the manuscript.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Clinical Trails

Not applicable.

Competing interests

The authors have no competing interest to disclose.

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