PRINT ISSN 1119-8362
Electronic ISSN 2659-1499

Full-text Available Online at
https://www.ajol.info/index.php/jasem
https://www.bioline.org.br/ja

J. Appl. Sci. Environ. Manage.
Vol. 29 (12) 3713-3725 Dec. 2025

Microplastics in Soil Systems: The Overlooked Dimension of Plastic Pollution

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SUMMARY: This literature reviews evaluate existing research on microplastics in soil systems, highlighting microplastics as an overlooked yet important dimension of global plastic pollution. Microplastics, defined as plastic particles smaller than 5mm, have emerged as a significant environmental pollutant with growing concern. They originate from the degradation of larger plastic waste or are manufactured as micro-sized particles. The literatures used in the study were selected through a structured search of several academic databases including Google Scholar, SpringerLink, Science Direct, PubMed, ScienceOpen, and Elsevier. Evidence indicates that microplastics are persistent in soil environments, capable of interacting with its components, leading to changes in its physical and chemical characteristics, structure, nutrient cycling, microbial diversity and enzyme activities, and potentially affecting plant growth and productivity. This review examines the major sources of soil microplastics, including agricultural practices, wastewater irrigation, sewage sludge application, atmospheric deposition and land-based litter fragmentation. The role of microplastics as vectors for antibiotics, heavy metals, and other toxic substances is also discussed, emphasizing possible implications for soil health, food security, and ecosystem balance. It also examines strategies for effective mitigation of microplastic contamination in soils. Addressing this underexplored dimension of plastic pollution is essential for maintaining soil quality, protecting ecosystems, and promoting environmental sustainability amid rising plastic production and use.

DOI: https://dx.doi.org/10.4314/jasem.v29i12.6

Cite this Article as: UCHENNA, U. F; IHEUKWUMERE, I; UGBOGU, O. C. (2025). Microplastics in Soil Systems: The Overlooked Dimension of Plastic Pollution. *J. Appl. Sci. Environ. Manage.* 29 (12) 3713-3725

Dates: Received: 30 October, 2025; Revised: 27 November 2025; Accepted: 23 December 2025; Published: 31 December 2025

Keywords: Plastic particles; Soil Ecosystems; Environmental Pollutant; Plastic Degradation; Pollution mitigation

The global environment faces increasing contamination from emerging pollutants, particularly microplastics (Richardson and Kimura, 2017). Plastics, synthetic polymers derived from petroleum or gas, are widely used due to their affordability, durability, and versatility across sectors such as agriculture, packaging, construction, and healthcare. Global plastic production reached 460 million tons in 2019 and is projected to triple by 2060 without regulatory action (OECD, 2022). The COVID-19 pandemic escalated plastic production due to amplified demand for plastic-based protective materials. However, only about 9% of plastics are recycled, while the rest persist in the environment due to their chemical stability and resistance to degradation (OECD, 2022). Inefficient waste management accelerates their accumulation and fragmentation into microplastics. Nigeria is a major contributor in the plastic economy, with production increasing from 0.6 million tonnes in 2004 to 1.3 million tonnes in 2024 (Animashaun *et al*., 2025). Between 1996 and 2017, about 20 million tonnes

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were imported, with projections of 40 million tonnes by 2030 (Ezeudu *et al*., 2024). The country accounts for roughly 63% of West Africa's plastic resin imports, yet recycles less than 12% of its plastic waste, most of which ends up in landfills with prolonged decomposition times.

Microplastics which are plastic particles 5mm or smaller, occur as microbeads, fibers, pellets, and fragments (Kosuth *et al*., 2018). Their small size, hydrophobicity, and large surface area enable them to adsorb and transport pollutants across soil, aquatic, and atmospheric systems (Yang *et al*., 2021). They are classified as primary, intentionally manufactured in small sizes (e.g. microbeads and pellets in cosmetics and industrial processes), and secondary, generated from the degradation of mesoplastics (5mm-25mm) and macroplastics (>25mm) (Anbumani and Kakkar, 2018).

In soils, microplastics alter microbial communities, soil structure, and plant growth (Bansal *et al*., 2021). Pollution levels are influenced by transformation processes, human activity, and land use (Chen *et al*., 2024). Their persistence, widespread use, and poor disposal make them a critical environmental threat (Moreno-Jiménez *et al*., 2022). Although several countries have introduced environmental regulations, enforcement remains weak, allowing pollution to intensify (Ebere *et al*., 2019). This research provides a holistic evaluation of microplastic contamination in soil environments, examining sources, distribution, interactions with pollutants, ecological effects, and mitigation strategies.

METHODOLOGY

This study is a literature review conducted using evidence-based reporting standards for review articles. The methodology was structured in line with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure transparency, reproducibility, and methodological soundness.

Selection of Literature: The literatures in this review were selected through a systematic search across multiple academic databases. The databases used for the search were Google Scholar, SpringerLink, Science Direct, PubMed, ScienceOpen, and Elsevier. Keywords used include: plastic particles, microplastics, soil ecosystems, environmental pollutant, soil structure, toxic substances, soil pollution, plastic degradation, environmental sustainability, and pollution mitigation. The search covered peer-reviewed articles published in English.

Inclusion Criteria:

Studies were included if they focused on microplastics in soil or other terrestrial environments, reported on their sources, distribution, transport, ecological effects, or interactions with pollutants, were peer-reviewed Journal articles, employed quantitative, qualitative, or mixed-method approaches, and were published in English.

Exclusion Criteria:

Studies were excluded if they were non–peer-reviewed publications or newspaper articles, focused exclusively on aquatic or marine environments without relevance to soils, or lacked sufficient methodological or analytical detail.

Selection Process:

The literature selection followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework:

Identification- Initial database searches were conducted and duplicate records were removed.
Screening- Titles and abstracts were screened for relevance to the review objectives.
Eligibility- Full texts of relevant articles were assessed against the inclusion/exclusion criteria.
Inclusion- Studies that met all criteria were selected for in-depth review and analysis.

OUTCOME

Sources and Distribution Of Microplastics In Soil Ecosystem: Soil is a vital natural resource that provides numerous essential ecosystem services supporting humans and other living organisms. However, various human activities such as plastic mulching, sewage irrigation, application of soil amendments, and improper waste disposal, along with environmental pathways like surface runoff and atmospheric deposition, have turned soil into a major reservoir of microplastics (Bian *et al*., 2022). A schematic diagram of sources of microplastics in soil ecosystem is shown in Figure 1.

Compost and sludge, commonly used to enhance soil fertility due to their high organic carbon and nutrient content, often contain significant amounts of microplastics (Bläsing and Amelung, 2018). Bläsing and Amelung (2018) found that applying compost at rates of 7 t/ha and 35 t/ha introduced microplastics at levels of 0.016–1.2 kg/ha and 0.08–6.3 kg/ha, respectively. This suggests that microplastic contamination correlates with the frequency and quantity of organic amendments applied. Similarly, Gao *et al*. (2019) reported an average microplastic concentration of 1.2 g/kg in compost-amended soils.

Plastic film mulching, widely used to enhance crop yields, is another major contributor (Miao *et al*., 2024). Weathering, UV exposure, and mechanized farming break down plastic films into microplastics, which then enter the soil due to poor recovery and recycling (Qadeer *et al*., 2021). Huang *et al*. (2020) found microplastic levels of 0.1–324.5 kg/ha in mulched soils after analyzing 384 samples.

Irrigation with treated or untreated wastewater is also a significant source, especially in water-scarce regions. Globally, about 20 million hectares of farmland are irrigated with such water, having impact on the food supply for 10% of the World's population (Carter *et al*., 2019). Even after treatment, sewage retains at least 1% of its microplastic content (Bodzek *et al*., 2024). Microplastics in the influent were largely removed, achieving an efficiency of about 96%. Nevertheless, a large quantity of microplastics, about 2.87×10^8 particles per day, were still released through the effluent and excess sludge (Zhang *et al*., 2021). These microplastics originate from personal care products, textiles, and surface water sources commonly used for irrigation.
Airborne microplastics are deposited onto soil via atmospheric transport and rainfall (Zhang *et al*., 2020). Surface runoff then carries them into deeper layers (He *et al*., 2018). Dris *et al*. (2016) reported that 3–10 tons of fibrous microplastics can accumulate in an area annually through air deposition. Other sources include tire wear, littered plastic waste, synthetic fibers from laundry, and packaging materials for fertilizers and agrochemicals (Wang *et al*., 2020).
The migration and retention of microplastics in soil are influenced by factors like soil structure, biota, management practices, and weather (Zhang *et al*., 2019). Cracks and macropores facilitate their entry, while biological and seasonal factors aid their distribution. These particles absorb harmful chemicals, contributing to soil pollution and altering its properties, which negatively impacts ecosystem health (Zhang *et al*., 2022).

Microplastic concentration typically decreases with soil depth. In Shanghai, China, Liu *et al*. (2018) recorded 78.0 kg^{-1} in surface soil and 62.5 kg^{-1} in deeper layers. Yu *et al*. (2021) also found higher concentrations at 10-25cm depth compared to 0-5cm, with sandy soils holding more microplastics than clay or loam. Various studies have quantified microplastics in soils. Scheurer and Bigalke (2018) detected 55.5 mg/kg in Swiss floodplains. Corradini *et al*. (2019) reported 0.57–12.9 mg/kg in Chilean farmland treated with sludge; and Zhou *et al*. (2018) measured 712.5 mg/kg in coastal soil from Shandong, China.

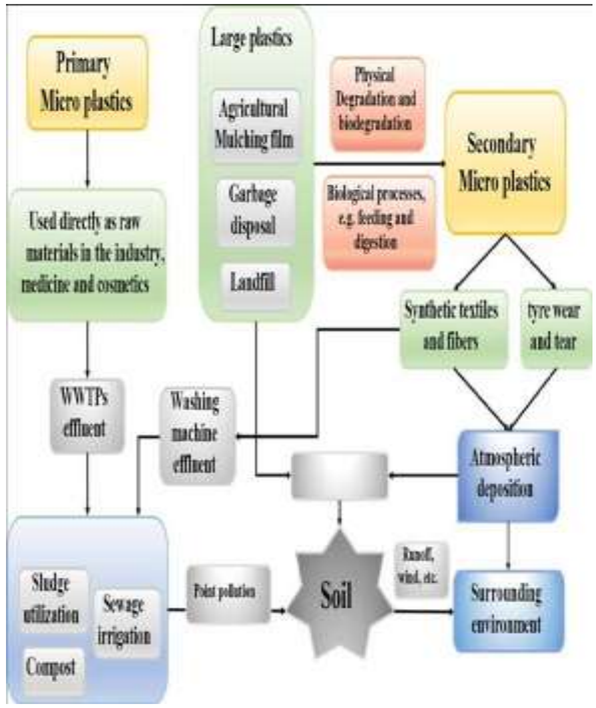

Fig. 1: Schematic diagram of the sources of microplastics in soil ecosystem (Source: Yu *et al*., 2022)

Impact of Microplastics On Soil Properties And Biota
Effects on physicochemical properties and nutrients: Microplastics modify soil's physical and chemical characteristics, influencing pH, nutrient dynamics, organic matter, porosity, water retention, bulk density, and aggregate stability (Ya *et al*., 2021). They can alter soil pH through acid release from degrading aliphatic polyesters, interactions with soil ions, and changes in microbial communities, such as reduced ammonia-oxidizing bacteria (Yu *et al*., 2021; Zhao *et al*., 2021). Depending on soil type, plastics like polyethylene may increase pH in alkaline soils or lower it in acidic ones, thereby affecting microbial activity and nutrient availability (Qi *et al*., 2020; Dissanayake *et al*., 2022).

Microplastics alter soil porosity and bulk density, with effects varying by polymer type, shape, and concentration (Zhang *et al*., 2019). Changes in porosity can accelerate evapouration and cause cracking (Wan *et al*., 2019), while variations in bulk density influence aeration, compaction, and water flow (Kim *et al*., 2021). They also affect soil aggregate stability, leading to redistribution of aggregate sizes and reduced biological activity (Huang *et al*., 2022).

Water retention may either increase or decrease depending on polymer type. For instance, polyester fibers increased water-holding capacity, while polyacrylic fibers reduced it (Lehmann *et al*., 2019; Sajjad *et al*., 2022). Microplastics can also increase soil temperature by enhancing solar absorption and trapping air between particles (Amare and Desta, 2021). Additionally, they reduce hydraulic conductivity and disrupt organic matter dynamics by clogging pores and destabilizing aggregates (Qi *et al*., 2020; Zhang and Zhang, 2020).

Microplastic contamination hinders aggregate formation and microbial decomposition of organic matter, reducing CO_2-fixing microbes such as *Chloroflexi aurantiacu*s and overall fertility (Liu *et al*., 2021; Abbott *et al*., 2022). Their weak functional groups and low crystallinity limit cation exchange, increasing heavy metal bioavailability (Li *et al*., 2021). Microplastics in soil can alter nutrient availability by adsorbing essential elements like potassium, phosphate, and nitrogen, thereby reducing their uptake by plants. This can lead to decreased plant growth and yield, posing risks to agricultural productivity and food security (Dong *et al*., 2021; Yu *et al*., 2021).

Effects on soil enzyme activities: Soil enzymes regulate key nutrient cycles (carbon, nitrogen, and phosphorus) and act as sensitive indicators of soil fertility and ecosystem shifts (Wang *et al*., 2022). Microplastics significantly alter the activities of enzymes such as phenol oxidase, catalase, fluorescein diacetate hydrolase (FDAse), and urease, with effects depending on polymer type, size, concentration, exposure duration, and environmental conditions (Huang *et al*., 2019). A decline in the activities of urease, fluorescein diacetate hydrolase (FDAse), and dehydrogenase has been reported in soils containing microplastics. However, high concentrations (28% w/w) stimulated FDAse and phenol oxidase, while lower levels (7% w/w) showed minimal effects (Yu *et al*., 2021). Similarly, low microplastic inputs decreased phosphatase activity without affecting catalase or urease (Feng *et al*., 2022). These differences could be related to the varied concentrations and polymer types used in the studies. Temporal variation also occurs. Polyamide reduced catalase, β-glucosidase, and urease within 20 days, but effects diminished by day 70 (Chen *et al*., 2020). Polymer type strongly influences enzyme responses. Polyethylene enhanced urease and catalase but had little impact on sucrase, whereas polyvinyl chloride and polyethylene inhibited FDAse while stimulating acid phosphatase and urease in acidic soils (Fei *et al*., 2020a).

Effects on soil microbial communities: Microplastics significantly alter the composition, diversity, and activity of soil microbial communities by disrupting soil physicochemical and nutritional properties (Judy *et al*., 2019). Changes in enzyme activity further indicate shifts in microbial function and substrate availability (Fei *et al*., 2020b). Microbial biomass, diversity, and activity often decline with microplastic contamination, reducing nutrient availability and plant productivity (Azeem *et al*., 2021; Santini *et al*., 2023). The extent of impact depends on polymer type, concentration, soil conditions, and exposure duration. Polyethylene and polyvinyl chloride both decreased microbial diversity, with stronger effects from polyethylene (Fei *et al*., 2020a). Low microplastic levels suppressed microbial activity, while higher concentrations stimulated it (Kumar *et al*., 2020). Microbial abundance initially increased but declined with prolonged exposure (Ren *et al*., 2020). Some microorganisms adapt by colonizing microplastic surfaces, forming biofilms, and utilizing degradation products as carbon sources (Yu *et al*., 2021; Xie *et al*., 2021). Enrichment of genera such as *Pseudomonas*, *Bacillus*, and *Aspergillus* has been reported in response to certain biodegradable polymers like poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (Zhou *et al*., 2021). These biofilm-associated microbes influence biogeochemical processes, altering carbon and sulphur cycling (Zhang *et al*., 2021). Microplastics also modify soil aeration, porosity, and moisture, affecting aerobic and anaerobic microorganisms (De Souza Machado *et al*., 2018). Combined pollution from microplastics and heavy metals (e.g., cadmium) disrupts microbial interactions, reducing arbuscular mycorrhizal colonization and nutrient cycling (Wang *et al*., 2020). Chen *et al*. (2022) observed that polylactic acid altered microbial interactions in soil, affecting nitrogen fixation and mineral uptake. Even at low concentrations (0.5%), microplastics impaired gut microbial communities in springtail microarthropods (Ju *et al*., 2019). Zhu *et al*. (2018) similarly found altered gut bacteria in *Folsomia candida* after 56 days of microplastic exposure. Reduced enzyme activity and soil respiration under microplastic exposure such as decreased CO_2 emissions from polyethylene-contaminated soils, further demonstrate suppressed microbial activity and deteriorating soil health (Zhao *et al*., 2021; Irving *et al*., 2024).

Effects on soil animals: Exposure to microplastics disrupts the activity of key soil fauna such as earthworms, springtails, mites, and amoebas, impairing their ecological roles and overall soil health (Jeong *et al*., 2024). Reported effects include reduced survival and growth, oxidative stress, immune dysfunction, energy depletion, DNA damage, and abnormal gene expression (Möhrke *et al*., 2022; Ya-di *et al*., 2022). Ya-di *et al*. (2022) found that earthworms exposed to 0.2–1.2% microplastics showed increased mortality and growth inhibition, while higher concentrations (1–20%) induced lipid peroxidation and tissue damage. Similarly, tire-derived microplastics reduced springtail reproduction and survival by 38% and 24%, respectively (Selonen *et al*., 2021). These biological disturbances can be transferred through the food chain, threatening agroecosystem stability (Chen *et al*., 2025). The primary mechanism of toxicity involves microplastic accumulation in digestive tracts, impairing feeding, development, and immune responses (Zhang *et al*., 2019). The extent of harm depends on particle shape, size, polymer type, concentration, and additives (Li *et al*., 2021). Polyethylene terephthalate (PET) caused gastrointestinal damage and oxidative stress in snails (Song *et al*., 2019), while in earthworms, ingestion of polyethylene and polystyrene particles led to intestinal injury, reduced enzyme activity, DNA damage, and impaired reproduction (Jiang *et al*., 2020; Xiao *et al*., 2022). Similarly, Lu *et al*. (2018) observed that mice exposed to microplastics experienced reduced mucin secretion and disrupted liver lipid metabolism.

Effects on plants: Plants are exposed to microplastics through plastic mulching, sewage sludge, and organic manure applications, leading to disruptions in physiological and biochemical functions. Reported effects include altered root traits, reduced germination and yield, oxidative stress, genotoxicity, impaired growth, and reduced photosynthetic activity (Hernández-Arenas *et al*., 2021).

Microplastics induce both direct and indirect impacts. Direct effects include adsorption of particles onto roots, altering morphology and hindering water and nutrient uptake (Jiang *et al*., 2019). They also cause tissue damage, oxidative stress, and reduced uptake of essential micronutrients such as manganese, zinc, iron, and copper (Lian *et al*., 2020). Indirectly, they modify soil properties, increasing evapouration, reducing microbial diversity, and diminishing rhizosphere fungal symbionts, which lower plant diversity (Wan *et al*., 2019).

Experimental evidence shows that 1% low-density polyethylene in soil suppresses wheat growth (Qi *et al*., 2018). Polylactic acid reduced maize chlorophyll and biomass and, when combined with polyethylene, altered arbuscular mycorrhizal fungi diversity while increasing soil pH and cadmium levels (Wang *et al*., 2020). Likewise, polylactic acid and high-density polyethylene reduced ryegrass biomass, height, and germination (Boots *et al*., 2019).

Microplastics As Vectors Of Other Environmental Pollutants: Microplastics serve as surfaces for the sorption of various organic contaminants. Sorption refers to the combined processes of adsorption (attachment of molecules to a surface via forces such as van der Waals or covalent bonds) and absorption (uptake of molecules into the interior of a material, typically through weak van der Waals forces) (Fu *et al*., 2021). At low environmental concentrations, adsorption dominates due to strong surface interactions, whereas absorption prevails at higher concentrations because of the greater availability of chemical compounds for uptake (Fu *et al*., 2021).

Microplastics thus act as vectors for toxic pollutants, facilitating the transport, bioaccumulation, and biomagnification of lipophilic chemicals in food chains (Bhardwaj *et al*., 2024). Common sorbed pollutants include heavy metals, persistent organic pollutants (POPs) such as polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs), dichlorodiphenyltrichloroethane (DDTs), hexachlorocyclohexanes (HCHs); and polycyclic aromatic hydrocarbons (PAHs). Other emerging pollutants include pharmaceutical active compounds (PhACs), antibiotics, and UV filters (Tumwesigye *et al*., 2023).

Sorption mechanisms depend on the physicochemical interactions between microplastics and pollutants, influenced by hydrophobicity, polymer characteristics, and environmental factors (Agboola and Benson, 2021; Prajapati *et al*., 2022). Electrostatic forces also affect sorption of polar persistent organic pollutants. For instance, perfluorooctanesulfonate (PFOS) exhibits reduced sorption to polystyrene due to charge repulsion, whereas perfluorooctanesulfonamide (FOSA) binds more strongly because of aromatic ring interactions (Fatima *et al*., 2025).

Microplastics and antibiotics often co-exist in the environment, sharing similar sources and migration pathways. Their interaction enhances pollutant transport, modifies toxicity, and fosters antibiotic resistance and gene dissemination (Deans *et al*., 2023). Sorption processes are further regulated by environmental parameters (salinity, pH, organic matter, temperature, ionic strength) and microplastic properties such as size, shape, density, polymer type, crystallinity, and aging degree (Xia *et al*., 2023).

Prevention and Control Strategies: Microplastic pollution is hazardous due to its ability to alter physical, chemical, and biological processes, negatively affecting ecosystems. Prevention and control strategies include enforcing management policies, promoting biodegradable plastics, and regulating plastic reuse and disposal.

*Legislative regulations and initiatives***:** Global efforts to curb microplastic pollution have led to several regulatory actions. The European Union introduced rules targeting up to 65% recycled content in plastic bottles by 2040, restrictions on single-use packaging, bans on per- and polyfluorinated alkyl substances (PFAS) in food-contact materials, and improved labelling (Monnapule, 2024). The United States Environmental Protection Agency (EPA) launched a plan to eliminate plastic waste by 2040 through lifecycle producer responsibility, recycling enhancement, and circular economy promotion (Zhou and Luo, 2024).

In China, policies such as the *Plastic Restriction Order* (2000), *Opinions on Strengthening Plastic Pollution Control* (2020), and *Soil Pollution Prevention Laws* (2016–2018) promote biodegradable films and agricultural recycling (Liu *et al*., 2022; Yu *et al*., 2022). The Canadian government enacted the "Microbeads in Toiletries Regulations" in 2019 which prohibit the manufacture, import and sale of toiletries containing plastic microbeads (Akhbarizadeh *et al*., 2024). Italy, France, and Nigeria also implemented bans on non-biodegradable products and plastic bags (Adam *et al*., 2020; Choksy *et al*., 2022; Mghili *et al*., 2024).

Despite these efforts, weak enforcement, high costs, and limited alternatives hinder progress. Coordinated global policies are needed to regulate plastic use, encourage biodegradable innovations, and enhance waste management (Hettiarachchi and Meegoda, 2023).

Use of non-plastic products and biodegradable plastics: Reducing plastic use at the source is key to limiting microplastic buildup. Alternatives include glass, paper, or biodegradable materials, and designs that minimize plastic content (Walker, 2018). The 6Rs strategy: reuse, recycle, redesign, remanufacture, recover, and reduce, supports this goal. When conventional reduction is unfeasible, bioplastics or plant-based plastics can serve as substitutes (Serrano-Aguirre and Prieto, 2024).

However, their widespread use is limited by high production costs and operational challenges (RameshKumar *et al*., 2020). Adopting low-cost biodegradable additives and materials like cellulose microbeads or paper, jute, and cotton bags can enhance sustainability (Alteneiji *et al*., 2024).

Recycling and appropriate disposal of plastic wastes: Many countries have banned single-use plastics and expanded recycling initiatives to minimize environmental leakage (Adjama *et al*., 2024). Recycling transforms used plastics into raw materials, reducing waste and pollution (Darko *et al*., 2023). The process involves waste collection, separation, grinding, refining, and reintegration into production (Walker, 2018). Effective waste handling and prevention of direct dumping are vital. The COVID-19 pandemic increased single-use personal protective equipment (PPE) waste, emphasizing the need for careful management to prevent secondary pollution (Issac and Kandasubramanian, 2021).

Sustainable biological methods: Biodegradation using microorganisms offers an eco-friendly approach to microplastics removal. Species such as *Ideonella sakaiensis* and *Zalerion maritimum* utilize enzymatic pathways for degradation of polyethylene terephthalate (PET) and polyethylene (PE) (Sarmah and Rout, 2018). Optimized environmental conditions can enhance microbial breakdown, making bioremediation a sustainable method for reducing microplastic pollution (Tiwari *et al*., 2020).

Conclusion and Future Directions: This review provides an integrated evaluation of existing research on the presence, sources, and effects of microplastics in soil systems, emphasizing soils as both a major reservoir and secondary source of plastic pollution. Drawing on findings from a wide range of studies, the paper enhances understanding of the diverse pathways through which microplastics are introduced into terrestrial environments, including agricultural activities, wastewater irrigation, land application of sewage sludge, and atmospheric deposition. The review further explains how microplastics alter soil physicochemical properties, disrupt nutrient cycling, modify microbial community structure, and impair plant development. In addition, it highlights the ability of microplastics to act as carriers for other contaminants. Future research should focus on standardized methods for soil microplastic sampling and analysis to improve comparability across studies. Integrating scientific evidence with policy, sustainable agriculture, and circular economy frameworks will be vital for effective mitigation of soil microplastic pollution.

DECLARATIONS

Ethical Approval: This study did not involve human participants or animal experimentation and therefore did not require formal ethical approval. All procedures involving data handling and analysis were conducted responsibly and in accordance with standard academic and institutional guidelines.

Disclaimer (Artificial Intelligence): Authors hereby declare that no generative *Artificial Intelligence* (AI) technologies such as Large Language Models (ChatGPT, COPILOT, XLNet, Ernie 3.0 Titan etc) and text-to-image generators have been used during writing or editing of this manuscript.

Declaration of Conflict of Interest: The authors declare that no known conflict of interest or personal relationships that have influenced the work reported in this paper.

Declaration of Data Availability: Data sharing is not applicable to this article as no datasets were generated or analyzed.

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