Ecofarming (e-Magazine)
Agriculture

Ecofarming
e-Magazine for Agriculture and Allied Sciences
http://www.ecofarming.rdagriculture.in
e-ISSN: 2583-0791

Micro-plastics in Soil Ecosystem

Sources, Fate and Ecological Impacts

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Received: February, 2026; Accepted: March, 2026; Published: April, 2026

Micro-plastics are plastic particles having size smaller than 5 mm and are emerging contaminants in terrestrial ecosystems. These particles accumulate in terrestrial ecosystems from primary micro-plastic sources or from fragmentation of larger plastics. Growing evidences show that micro-plastics may disrupt soil physical conditions, alter chemical parameters, and interfere with functioning of microbiological communities, with downstream effects on soil health, crop performance and reduced agricultural productivity. Experimental findings also revealed changes in root morphology, compromised plant physiology, impaired symbiotic associations which ultimately lead to decreased crop productivity. Furthermore, the potential uptake and accumulation of micro- and nano-plastics into edible plant tissues raises food safety concerns. This article synthesizes current research on sources, transport mechanisms, further shedding light on their complex interactions with terrestrial components, dynamic fate and associated ecological impacts. It underscores the urgency for integrated monitoring, standardized methodologies including their interactions, assessment protocols, actionable mitigation recommendations and interdisciplinary research to safeguard soil resilience and sustainable crop production.

Sources of Micro-plastics in Agricultural Soil

Micro-plastics can enter to agricultural soils intentionally and unintentionally via multiple pathways: fragmentation of plastic mulches and films, contaminated irrigation water, agrochemical carriers, atmospheric deposition, fermented bio-solids and composts. In India, polyethylene films and untreated wastewater are major contributors. Using sewage sludge as an irrigation source can add about 4,196 to 15,385 micro-plastic particles per kilogram of the sludge. Micro plastic particles counts ranging from 14 to 895 per kilogram of dry weight compost were also observed. Untreated wastewater including detergents and effluents from personal care products contains micro plastics at a very high rate and using this wastewater for irrigation purposes can add micro plastics directly to the soil. Plastic film mulch provides many benefits: controlling weed growth, maintaining soil temperature, minimizing soil erosion, reducing evaporation and other water losses, preventing soil splashing, improving produce quality and yield. On another hand, plastic film mulch add micro plastics to soil because they are not readily biodegradable, and the abundance of MPs has also been reported in plastic film mulched soil compared to non-mulched soil. Burning of agricultural residues containing plastic waste may also contribute to airborne micro-plastic fallout. Atmospheric deposition of micro plastics through tire abrasion, deposition of industrial and consumer plastic waste is also reported in very remote places or at high mountains. Flooding can also cause the deposition of substantial amount of MPs in soil ecosystems. Mostly used plastic products ultimately add a wide range of MPs to the environment including high density polyethylene (HDPE), low density polyethylene (LDPE), linear low density polyethylene (LLDPE), bio degradable poly (3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV), polyethylene (PE), acrylic fibres (PP&A), poly vinyl chloride (PVC), polypropylene (PP), polyurethane (PUR), polystyrene (PS), poly tetra-fluorethylene (PTFE), poly ethersulfone (PES), polyethylene terephthalate (PET), synthetic blend rubber (SBR), polyurethane (PU), acrylonitrile butadiene styrene (ABS), styrene butadiene (SBR), expanded polystyrene (EPS), thermo-plastic elastomers (TPE), styrene-acrylonitrile copolymer (SAN), poly methyl methacrylate (PMMA), polycarbonate (PC), and polyamide (PA).

Fate of Micro-plastics in Terrestrial Ecosystems

Once introduced into soil systems, particles are redistributed via surface runoff, wind erosion or faunal activity, and undergo complex transformation and interactions as following:

- **Vertical transport**: Based on soil structures, MPs can move downward via agricultural practices like ploughing, preferential flow or desiccation cracking. Generally, these MPs can't reach the groundwater, but smaller particles and fibres may possibly migrate downward to the subsoil and groundwater reservoirs in coarse textured soils having high water table.
- **Bio-turbation and incorporation**: Soil fauna such as earthworms and insects redistribute micro-plastics vertically and horizontally, incorporating them into soil aggregates or deeper layers.
- **Surface accumulation**: Larger fragments and films tend to accumulate in surface layers, from where they may be mobilized by wind or with water.
- **Fragmentation and degradation**: Physical abrasion, tillage, UV exposure (in surface soils), and microbial activity fragment plastics, which increases particle number, environmental mobility and adsorption potential.
- **Sorption and desorption**: Micro-plastics act as carriers for hydrophobic organic compounds and metals, adsorbing them from soil solution and again releasing under changing soil and environmental conditions.
- **Plant uptake and translocation**: Nano- and micro-sized particles may be absorbed by plant roots; further trans-located and accumulated in aerial tissues; and ultimately enter into food chains.

Thus, these dynamic transport and transformation mechanisms underscore the need for integrated soil–air–water monitoring and lifecycle-based ecological studies to assess mobility, movements within soil profile, sorption, degradation, persistence, translocation and further associated contamination potential of micro-plastic in any agricultural eco-system.

Effects of Micro-plastics on Soil Properties and Ecosystem Functions

Micro plastics alter the soil microclimate and atmosphere by affecting soil's physical, chemical and biological properties.

- Micro-plastic fibres commonly increase soil porosity by creating channel-like structures, whereas rigid fragments and films can block pores and alter pore size distribution that changes infiltration rate and preferential flow. In addition, increased MPs may interfere with the accumulation of small soil particles, reducing micro-pores.
- Polyester fibres may increase water-holding capacity in loamy and sandy soils to some contexts but contradictory results are also observed in clay soil which indicates that MPs' negative effect exceeded the microspores' positive impact.
- The increasing MPs may decrease infiltration rate or solutes movement depending on particle size. Despite increasing the soil's surface area, small micro plastic particles might also increase its hydrophobic surface area, which induces water repellence and limit capillary flow.
- MPs may also reduce bulk density depending on the types of MPs e.g. incorporation of MPs like PS, PP, PET, PES, or HDPE show a decrease in soil bulk density compared to poly acrylic and polyethylene micro particles.
- Desiccation cracking in soil is a complex physical phenomenon affecting strength, stability, and permeability. Desiccation cracking is observed when large plastics are present and may be associated with water evaporation from the deep soil layers, leading to more dryness and harsh conditions for plant growth. Additionally, when water re-saturates the soil after cracking, plastics and other pollutants can migrate into deep soil layers along the crack.
- Incorporation of large MPs like microfibers (HDPE, polyester, and polyacrylic fibres) can decline water-stable soil aggregates, raising susceptibility to erosion and surface sealing under rainfall conditions.

- With a rise in micro plastic concentration (> 1%), the cohesion among micro plastics, soil particles, and aggregates could progressively result in the encasement of soil particles by micro plastics, a "wrapping" effect which reduces the interaction between soil particles. The formation of these "ineffective pores" through combination of soil and micro plastic particles could potentially displace the "effective pores" that naturally occur between soil particles, causing more air to replace the water in pores, further weakening water permeability.
- Micro plastics like PE can decrease soil sorption capacity, initiate the movement of organic contaminants, and cause soil hardening, which increases input costs. On positive perspective, these absorbed MPs will not be available to plants and soil biota for uptake.
- Depending on the type of MPs and soil nature, MPs can increase or decrease the soil pH e.g. PE lower soil pH in acidic soils whereas increase in alkaline soils. The tire debris can also raise soil pH, and HDPE can decrease it.
- Although, many polymers are chemically inert but readily absorb hydrophobic organic contaminants, pesticides, heavy metals, antibiotics, and other xenobiotics, thus acting as vectors for pollutant redistribution in soil profile. Furthermore, MPs can also act as a carrier for pathogens. This role of plastics as carriers for contaminants and pathogens may pose long-term ecological threats and health risks.
- Micro plastics can disrupt microbial habitats, affect their behaviour, and potentially lead to changes in soil biota composition, with widespread effects throughout the terrestrial food web.
- Plastic surfaces develop distinct microbial assemblages known as “plastispheres,” which differ in composition and function from surrounding soil micro-biomes and can include degraders and opportunistic taxa.
- Ingestion of micro-plastics by earthworms, collembolans, nematodes, and other soil fauna reduce their growth, reproduction, and bio-turbation activity, thereby diminishing organic matter mixing, soil structure maintenance, SOM mineralization rates and nutrient cycling dynamics, especially for nitrogen and phosphorus.
- Under long-term exposure scenarios, altered microbial communities are further associated with changes in extracellular enzymes activities, potentially slowing down fundamental processes vital to crop nutrition and overall soil fertility. Long-term uses of plastic mulch can down regulate the gene expression of crucial soil enzymes like DHA, glucosidase, urease etc.
- Micro plastics can increase the C:N ratio, which increases microbial immobilization.
- Plastic film mulch such as PE decreases the abundance of Proteobacteria and increases Actinobacteria.
- Additionally, micro-plastics may interfere with beneficial microbial symbioses, disrupt nutrient cycling, and reduce microbial diversity, which collectively impair soil resilience, suppress disease resistance, and compromise the ecological balance essential for sustainable agricultural productivity.

Impacts of Micro-plastics on Plant Physiological Responses

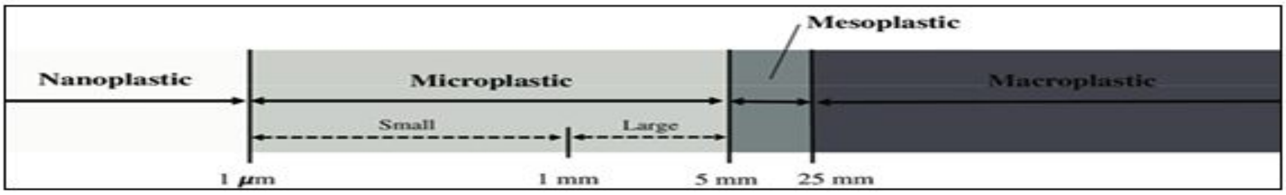
Micro plastics affect plants in different ways, encompassing reduced biomass, altered growth rate/responses, and modifications in crop productivity. In addition, micro plastics are bound to plant roots by adhesive secretions and accumulate near root-soil interfaces, leading to elevated concentrations of micro-plastics.

- The elevated micro-plastic concentrations at seedbed can reduce germination rates.
- Higher accumulation of micro-plastics in rhizosphere may alter root morphology, producing shorter, thicker roots.
- Retention of fibre-rich substrates impairs soil structure, especially in surface soil layers which creates mechanical impedance to root penetration.
- Disruption of rhizosphere microbiomes and mycorrhizal associations can reduce nutrient uptake efficiency, causing deficiency symptoms even when soil nutrient pools appear adequate.

- Hydraulic changes induced by micro-plastics modify plant-water relations; increased soil water retention in some cases transiently reduces drought stress, but uneven water distribution and pore blockage may reduce effective water availability or heighten water logging risk.
- Additives and leachates from polymers, including plasticizers and stabilizers, may produce phytotoxic responses such as reduced photosynthetic rate, chlorosis, and oxidative stress in plants.
- The uptake and translocation of micro- and nano-plastics into shoots and edible tissues of some crops is also reported, highlighting the potential pathways to food chain.
- Micro plastics disrupt the cycling of essential nutrients, potentially causing a 14% loss in yields for crops like corn and rice.

Conclusion

Micro plastics are an emerging global concern with potential repercussions for soil health and ecosystem integrity. Despite many benefits, plastics presence in the soil will have adverse effects on soil functioning, often with negative consequences for plant growth, although the effects vary with particle characteristics, concentration, and management context. Mitigating micro plastic pollution in soils requires a multi-faceted approach, including source reduction, standardized monitoring, developing effective removal technologies, regulatory frameworks, policy interventions, and public awareness campaigns. Practical measures also include safe disposal of agricultural films, screening of composts and bio-solids for plastic contamination, upgrading wastewater and sludge treatment, and adopting certified biodegradable mulches only where lifecycle assessments support net benefit. The studies investigating the environmental impacts of micro-plastics must explore a diverse spectrum of micro-plastics with varying origins and functions, and their interaction with soil, organisms, and plants performance. Research priorities should include long-term field trials across diverse agro-ecosystems and standardized monitoring protocols to link mechanistic studies of nano-scale uptake pathways, and assessment of combined stressors (micro-plastics plus agrochemicals or salinity) on soil biota and plant performance. Addressing the micro-plastic challenge will require inter-disciplinary collaboration among soil scientists, agronomists, policymakers, and waste-management authorities for preserving soil health and safeguarding agricultural productivity and ensuring a sustainable future.



Classification of plastics according to size (GESAMP, 2016)