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Microplastics and Nanoplastics in Agricultural Soils: Sources, Fate, Impacts, and Management Strategies

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Plastic pollution has emerged as a major environmental concern worldwide. Agricultural soils are increasingly recognized as significant sinks for microplastics (MPs, <5 mm) and nanoplastics (NPs, <1000 nm), originating from agricultural activities, wastewater irrigation, sewage sludge application, and atmospheric deposition [1,2]. These contaminants can alter soil physicochemical properties, disrupt microbial communities, affect nutrient cycling, and influence crop productivity [3,4]. Nanoplastics present additional concerns because of their ability to penetrate biological tissues and enter food chains [5]. This review summarizes the major sources, environmental fate, ecological impacts, and management strategies associated with MPs and NPs in agricultural soils.

Keywords: Microplastics, Nanoplastics, Agricultural soils, Soil health, Soil microbiome, Sustainable agriculture

Introduction

The rapid increase in global plastic production has led to widespread environmental contamination. While research initially focused on marine ecosystems, agricultural soils have recently been identified as major reservoirs of microplastics and nanoplastics [1]. These particles originate from plastic mulches, irrigation systems, sewage sludge, composts, and atmospheric deposition [2]. Microplastics are defined as plastic particles smaller than 5 mm, whereas nanoplastics are generally less than 1000 nm in size [5]. Their persistence and widespread distribution raise concerns regarding soil health, crop productivity, and food safety [3].

Sources of Microplastics and Nanoplastics in Agricultural Soils

Plastic Mulching: Plastic mulch films are widely used to improve crop productivity. Continuous weathering and fragmentation of these materials contribute significantly to microplastic accumulation in agricultural soils [6].

Sewage Sludge and Biosolids: Wastewater treatment plants retain large quantities of plastic particles in sewage sludge. Application of sludge as fertilizer introduces MPs and NPs into agricultural lands [4].

Wastewater Irrigation: Treated and untreated wastewater used for irrigation contains plastic particles that can accumulate in soils over time [2].

Compost and Organic Amendments: Municipal composts may contain plastic residues originating from improperly segregated wastes, thereby serving as a source of contamination [7].

Atmospheric Deposition: Microplastics can be transported by wind and deposited in agricultural fields far from their original sources [8].

Fate and Transport of Microplastics and Nanoplastics in Soil

The fate and transport of microplastics (MPs) and nanoplastics (NPs) in agricultural soils are governed by a complex interplay of physical, chemical, and biological processes. Once introduced into the soil environment, plastic particles do not remain static; instead, they undergo continuous transformation, redistribution, and interaction with soil components. These processes determine their persistence, mobility, ecological effects, and potential entry into terrestrial food webs [3].

Fragmentation and Degradation Processes: Microplastics entering agricultural soils often originate from the breakdown of larger plastic materials such as mulch films, irrigation pipes, greenhouse covers, and packaging materials. Environmental factors including ultraviolet (UV) radiation, temperature fluctuations, mechanical tillage, and microbial activity contribute to the progressive fragmentation of plastics into smaller particles [6]. Photodegradation induced by sunlight causes oxidation of polymer surfaces, resulting in the formation of cracks and increased brittleness. Agricultural practices such as plowing, harrowing, and harvesting further accelerate physical fragmentation. Over time, these processes generate secondary microplastics and eventually nanoplastics, which possess greater mobility and biological availability [3]. Although complete biodegradation of conventional plastics is extremely slow, certain microorganisms have demonstrated limited capacity to degrade polymers such as polyethylene and polypropylene. However, under normal field conditions, degradation rates remain insufficient to prevent long-term accumulation in soils [7].

Interactions with Soil Components: After entering the soil matrix, MPs and NPs interact with minerals, organic matter, water, and living organisms. Soil texture and composition strongly influence the behavior of plastic particles. Fine-textured soils with higher clay and organic matter contents tend to retain more microplastics due to increased surface interactions and aggregation processes [10]. Plastic particles may adsorb soil organic matter, dissolved organic compounds, and mineral colloids, resulting in the formation of eco-coronas. These surface coatings alter particle density, charge, hydrophobicity, and mobility. The adsorption of nutrients and contaminants onto plastic surfaces further influences their environmental behavior [3]. Nanoplastics exhibit particularly strong interactions because of their large surface area-to-volume ratio. Their surface properties allow them to bind readily with soil colloids, influencing aggregation, sedimentation, and transport processes [5].

Vertical Movement Through Soil Profiles: The downward movement of plastic particles through soil profiles is influenced by particle size, shape, density, and soil hydraulic properties. Larger microplastics generally accumulate in surface layers because of limited mobility. In contrast, smaller particles and nanoplastics can migrate to deeper soil horizons through infiltration and preferential flow pathways [2]. Rainfall and irrigation events facilitate the transport of plastic particles into subsurface layers. Macropores created by plant roots, earthworms, and soil cracks serve as channels that accelerate downward movement. Studies have detected microplastics at depths exceeding 50 cm in agricultural soils, indicating that long-term accumulation may not be restricted to surface horizons [4]. Nanoplastics exhibit even greater mobility due to their colloidal characteristics and may eventually reach groundwater systems. This raises concerns regarding contamination of underground water resources and broader environmental dissemination [5].

Horizontal Transport and Redistribution: In addition to vertical movement, plastic particles may be redistributed horizontally through surface runoff, wind erosion, and agricultural operations. During heavy rainfall events, microplastics present in surface soils can be transported into nearby streams, rivers, and reservoirs [9]. Wind erosion represents another important transport mechanism, particularly in dry agricultural regions. Lightweight plastic fragments and fibers can become airborne and travel considerable distances before deposition. This process contributes to the widespread occurrence of microplastics in remote terrestrial environments [8]. Agricultural machinery can further facilitate horizontal redistribution by moving contaminated soil particles across fields. Consequently, even areas with limited direct plastic inputs may become contaminated over time.

Biological Transport (Bioturbation): Soil organisms play a significant role in the redistribution of microplastics and nanoplastics. Earthworms, termites, ants, nematodes, and other soil fauna ingest plastic particles during feeding activities and subsequently transport them within soil profiles [9]. Earthworms are particularly important ecosystem engineers. Their burrowing activities create channels that enhance water infiltration and facilitate the movement of plastic particles into deeper soil layers. Ingestion and excretion of MPs by earthworms can alter particle size distribution and increase their incorporation into soil aggregates [9]. Plant roots also influence plastic transport. Root growth can create pathways for particle movement, while root exudates may modify particle aggregation and retention within the rhizosphere. Recent studies suggest that nanoplastics may enter root tissues through cracks, intercellular spaces, and apoplastic pathways [5].

Aging and Surface Modification: As plastics remain in soil environments, they undergo aging processes that significantly alter their physical and chemical characteristics. Aging is driven by exposure to sunlight, oxygen, moisture, temperature variations, and microbial colonization [3].

Aged plastic particles typically exhibit:

- Increased surface roughness.
- Formation of cracks and pores.
- Higher oxygen-containing functional groups.
- Greater adsorption capacity for pollutants.

These changes enhance interactions with soil minerals, nutrients, heavy metals, pesticides, and microorganisms. Consequently, aged microplastics often display environmental behaviors that differ substantially from those of newly introduced particles [3].

Role as Carriers of Contaminants: Microplastics and nanoplastics can act as vectors for various environmental contaminants. Their hydrophobic surfaces readily adsorb heavy metals, pesticides, antibiotics, and persistent organic pollutants from surrounding environments [3]. Once contaminants are attached, plastic particles may transport them through soil profiles and across ecosystems. This carrier effect can increase contaminant persistence and bioavailability, potentially amplifying ecological risks. Furthermore, microbial pathogens may colonize plastic surfaces, creating mobile reservoirs of harmful microorganisms within agricultural systems [9].

Long-Term Persistence in Agricultural Soils: One of the most concerning characteristics of MPs and NPs is their persistence. Most conventional plastics require decades to centuries for complete degradation. Continuous agricultural inputs from mulching films, wastewater irrigation, compost application, and atmospheric deposition can result in progressive accumulation over time [1]. The long residence time of plastics means that even relatively small annual inputs may eventually lead to substantial contamination levels. As plastic particles become increasingly fragmented into nanoplastics, their detection becomes more difficult while their potential ecological impacts may increase.

Effects on Soil Properties and Microbial Communities

Microplastics can alter soil bulk density, aggregate stability, porosity, and water-holding capacity [10]. These changes affect root development and nutrient availability. Plastic particles also influence soil microbial communities by modifying habitat conditions and creating surfaces for microbial colonization. Changes in microbial diversity and enzyme activity may affect nutrient cycling and soil fertility [3].

Impact on Plants and Food Safety

Both MPs and NPs can affect seed germination, root growth, and plant physiological processes. Recent studies suggest that nanoplastics can enter root tissues and translocate to aerial plant parts, raising concerns about food chain contamination and human exposure [5]. Indirect effects on plants may arise from altered soil structure and disruptions to beneficial plant–microbe interactions [10].

Environmental and Human Health Implications

Microplastics can adsorb contaminants such as heavy metals, pesticides, and persistent organic pollutants, acting as vectors for their transport within soil ecosystems [3]. The accumulation of MPs and NPs in crops may ultimately increase human exposure through food consumption [5]. Although the long-term health effects remain uncertain, laboratory studies indicate potential risks including oxidative stress, inflammation, and cellular toxicity [5].

Mitigation and Management Strategies

Effective management of plastic pollution in agricultural soils requires:

- Reduction in single-use agricultural plastics.
- Adoption of biodegradable mulch materials.
- Improved recycling and disposal systems.
- Monitoring of sewage sludge and compost quality.
- Development of plastic-degrading microbial technologies.

Sustainable agricultural practices combined with regulatory measures are essential to minimize future contamination [6].

Conclusion

Agricultural soils are increasingly recognized as important sinks for microplastics and nanoplastics. These contaminants originate from multiple sources and can influence soil properties, microbial communities, plant growth, and environmental quality. Although research has expanded rapidly, significant knowledge gaps remain regarding long-term ecological and human health impacts. Continued research and improved management practices are necessary to ensure sustainable agricultural production and soil health.

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