# Impacts of Combined Microplastic and Heavy Metal Contamination on Soil Physicochemical Properties and Microbial Communities

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**Abstract** This paper provides a comprehensive review of the adsorption-desorption behaviors of microplastics and heavy metals, as well as their combined effects on soil physicochemical properties and microbial communities. Microplastics can bind heavy metals through mechanisms such as electrostatic adsorption and surface complexation, with the interaction process being modulated by factors including microplastic type, particle size, dosage concentration, and degree of aging. The combined contamination of microplastics and heavy metals not only alters soil physicochemical properties but also, through synergistic toxicity, reduces soil microbial diversity, reshapes community structure, disturbs soil enzyme activities and biogeochemical cycles of carbon, nitrogen, and phosphorus, thereby undermining the ecological stability of soil microbial systems. Current research mainly relies on short-term laboratory simulations, and there remains a limited understanding of the long-term ecological effects and the coupling mechanisms between physicochemical property evolution and microbial responses. Future efforts should prioritize *in situ* long-term monitoring and deepen the ecological risk assessment of combined contamination.

**Key words** Microplastics, Heavy metal, Soil properties, Microbial communities, Combined contamination

## 0 Introduction

Once plastic waste enters the environment, it gradually breaks down into microplastics through physical, chemical, and biological processes. Meanwhile, intensive industrial and agricultural activities, such as wastewater irrigation and mining/industrial effluent discharge, introduce substantial amounts of heavy metals into soils, where they co-exist with microplastics over extended periods, giving rise to combined contamination. Microplastics can immobilize heavy metals via adsorption and complexation; however, they also disrupt soil structure and alter the acid-base environment, thereby enhancing the mobility of heavy metals and inducing synergistic toxicity. Soil physicochemical properties are critical determinants of soil fertility, while soil microorganisms drive the biogeochemical cycling of carbon, nitrogen, and phosphorus, both serving as key indicators for assessing soil ecological health. Existing research has largely focused on the ecological risks posed by either microplastics or heavy metals individually, leaving the coupling mechanisms between soil physicochemical properties and microbial communities under combined microplastic-heavy metal stress poorly understood. In this context, this paper reviews the adsorption-desorption characteristics of heavy metals onto microplastics, and synthesizes the stress patterns of combined pollution on soil physicochemical properties and microbial communities, aiming to provide a reference for risk assessment and remediation strategies for combined contamination in soil environments.

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## 1 Adsorption-desorption characteristics of heavy metals on microplastics in soil

Microplastics can serve as carriers for heavy metals, primarily adsorbing heavy metal ions through electrostatic adsorption and surface complexation. In addition, microplastics can competitively adsorb with soil colloids, occupying active adsorption sites on the soil solid surface, thereby prompting the release of a portion of soil-adsorbed heavy metals back into the liquid phase and altering the chemical speciation of heavy metals[1]. Microplastics can reduce the retention capacity of soil solids for various heavy metals, thereby enhancing the desorption potential of heavy metals in soil and their mobility toward the liquid phase[2-3]. The adsorption-desorption interplay between microplastics and heavy metals in the soil environment is a complex process involving multiple synergistic mechanisms, among which direct interfacial adsorption plays a dominant role.

Oxygen-containing functional groups on the surface of microplastics, such as hydroxyl and carbonyl groups, can also form stable bindings with heavy metals through complexation and ion exchange, with the adsorption rate and binding strength being governed by kinetic behaviors including intraparticle diffusion and surface chemisorption[4-5]. Moreover, microplastics can indirectly modulate the adsorption-desorption equilibrium of heavy metals in soil, thereby altering their mobility and bioavailability. Upon entering soil, microplastics exert a physical displacement effect, disrupting soil aggregate structures and clogging soil pores[6]. They can also modify the soil acid-base environment, cation exchange capacity, and organic matter composition, consequently influencing the adsorption and desorption patterns of heavy metals[1]. In addition, microplastics can drive the transformation of heavy metal speciation in soil from a biological perspective by altering soil microbial communities and enzyme activities. Environmental factors such as soil ionic strength and redox conditions can also change

the surface properties of microplastics, synergistically affecting the adsorption and desorption processes of heavy metals[1,4].

The type, particle size, applied concentration, and aging degree of microplastics all influence their adsorption capacity for heavy metals. Under certain environmental conditions, polylactic acid and polyethylene exhibit higher adsorption capacities for heavy metals, whereas polystyrene, with its low content of oxygen-containing functional groups on the surface, shows relatively weak adsorption ability[4,6]. When microplastics are not encapsulated by soil components, smaller particle sizes provide more available adsorption sites, thereby enhancing their adsorption capacity for heavy metals[7]. The addition of microplastics at high concentrations reduces the soil's binding capacity for heavy metals, thereby increasing the environmental risk posed by heavy metal mobilization[4,6]. Natural aging and ultraviolet radiation render the surface structure of microplastics more complex and increase the number of oxygen-containing functional groups, which not only strengthens their adsorption capacity for heavy metals but also effectively inhibits desorption, thus enhancing the binding stability between microplastics and heavy metals[5,8].

## 2 Effects of combined microplastic-heavy metal contamination on soil properties

The combined contamination of microplastics and heavy metals can induce changes in soil physical and chemical properties. In heavy metal-contaminated soils amended with microplastics, soil water content was found to be significantly increased[9]. Compared with uncontaminated soil, soils contaminated with either heavy metals or microplastics alone, the combined contaminated soils exhibited a larger mean aggregate size[10]. The combined pollution also increased soil electrical conductivity, cation exchange capacity, and organic matter content, while decreasing soil pH[11-14]. However, studies by Zhang Xiaoqing[15] and Tang[9] reported that soil pH in the combined contaminated treatment was higher than that in uncontaminated soil. Conversely, Hou Ziyan[16] demonstrated that combined microplastic-heavy metal contamination led to reductions in soil electrical conductivity, cation exchange capacity, available nitrogen, and available phosphorus concentrations[16-17].

## 3 Effects of combined microplastic-heavy metal contamination on soil microbial communities

Combined microplastic and heavy metal contamination can alter microbial community structure and reduce diversity indices (Chao1 and Shannon), exhibiting a significant synergistic inhibitory effect[18-19]. The combined pollution of polypropylene and cadmium reduces microbial diversity in maize rhizosphere soil, with a decline in the relative abundance of Proteobacteria[20]. Biodegradable microplastics, specifically poly (3-hydroxybutyrate-co-3-hydroxyvalerate), can enhance bacterial α-diversity at low concentrations, but exhibit inhibitory effects at high concentrations[21-22]. The combined pollution of polyethylene and lead reduces microbial biomass, respiration rate, and the complexity of microbial community interaction networks, while simultaneously increasing the relative abundance of Proteobacteria[13]. The coexistence of microplastics and heavy metals can synergistically exacerbate disturbances to microbial communities, reducing microbial diversity and ecological network stability. This combined stress significantly enriches functional microbial groups that possess combined capabilities of heavy metal tolerance, metal reduction, and microplastic degradation, while simultaneously suppressing sensitive taxa and nitrogen-cycling microorganisms[23-24]. Combined microplastic-arsenic contamination has been shown to reduce the abundance of Proteobacteria while increasing the abundance of Chloroflexi and Acidobacteria[25]. Similarly, combined microplastic-cadmium contamination leads to an increase in Acidobacteria among bacteria, a decrease in Ascomycota and a significant increase in Basidiomycota among fungi, with fungi being more sensitive to the combined stress[10].

Combined contamination of microplastics and heavy metals alters soil microbial community structure and function, reduces microbial diversity and metabolic efficiency, restructures the composition of dominant microbial taxa, and interferes with carbon, nitrogen, and phosphorus cycling. It also modifies the activities of urease, invertase, and alkaline phosphatase, thereby disrupting core metabolic pathways in soil[26-27]. The combined pollution exhibits synergistic toxicity, enriching tolerant groups such as Actinobacteria, Proteobacteria, and Basidiomycota, while enhancing microbial oxidative stress and stress-resistance functions. Simultaneously, it suppresses sensitive taxa including arbuscular mycorrhizal fungi, thus weakening soil nutrient cycling and ecological stability[10,13,28].

## 4 Conclusions

Microplastics can undergo adsorption-desorption interactions with heavy metals, altering soil physicochemical properties, reducing microbial diversity, and affecting the structure and function of microbial communities. Compared with single-pollutant scenarios, the synergistic toxicity exhibited by combined contamination poses a greater threat to soil ecosystems. However, existing research remains largely confined to short-term laboratory simulations, leading to insufficient understanding of the long-term ecological effects of combined microplastic-heavy metal contamination in real environments. Moreover, the coupling mechanisms between the evolution of soil physicochemical properties and the microbial community responses driven by these two pollutants remain unclear. Therefore, further research is urgently needed in the future.

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