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Interactions among Heavy Metals, Microplastics and Pesticides in Soil and Advances in Microbial Remediation

Jiali Shao[1], Xinru Yuan[1] and Haihong Gu[2]

[1]College of Mining Engineering, North China University of Science and Technology, Tangshan 063210, China
[2]School of Enbironmental and Municipal Engineering, Tianjin Chengjian University, Tianjin 300384, China

Abstract: With the rapid development of intensive agriculture and the extensive use of agricultural inputs, soil environments are increasingly exposed to complex composite pollution dominated by heavy metals, microplastics (MPs), and pesticides. Microplastics, characterized by small particle size, large specific surface area, and strong hydrophobicity, can act as important carriers of various pollutants. Through adsorption–desorption processes, MPs significantly influence the migration, transformation, bioavailability, and ecological toxicity of heavy metals and pesticides in soil systems. Meanwhile, heavy metals and pesticides can also interact with each other, leading to synergistic, additive, or antagonistic effects that further complicate environmental behaviors and ecological risks. This review systematically summarizes the interaction mechanisms among heavy metals, microplastics, and pesticides in soil environments, focusing on adsorption–desorption behaviors, co-migration processes, and toxicity responses. The effects of physicochemical properties of MPs, pollutant characteristics, and environmental conditions on these interactions are discussed in detail. In addition, the current advances in microbial remediation technologies are reviewed, including microbial degradation of microplastics, microbial immobilization of heavy metals, and microbial degradation of pesticides. The roles of key functional enzymes, metabolic pathways, and microbial community interactions are also emphasized. Furthermore, the potential of microbial consortia and plant–microbe combined remediation strategies for treating composite pollution is highlighted, with particular attention to rhizosphere processes and synergistic mechanisms. Although significant progress has been made in understanding single or binary pollutant systems, studies on heavy metal–microplastic–pesticide composite pollution remain limited. Future research should focus on elucidating the synergistic mechanisms among multiple pollutants, improving the stability of microbial systems under complex stress conditions, and developing efficient, scalable remediation technologies. This review provides a theoretical basis for the risk assessment and remediation of composite pollution in agricultural soils.

Keywords: Microplastics; Heavy metals; Pesticides; Interaction mechanisms; Microbial remediation; Composite pollution.

1. Introduction

Agricultural intensification has significantly increased the input of fertilizers, pesticides, and plastic products such as mulching films, resulting in the accumulation of multiple pollutants in soil environments. Among these contaminants, heavy metals, microplastics (MPs), and pesticides have attracted increasing attention due to their persistence, toxicity, and widespread occurrence. Unlike single pollutants, these contaminants often coexist in soils, forming complex composite pollution systems with intricate physicochemical and biological interactions.

Microplastics are considered emerging contaminants that can adsorb and transport various pollutants due to their unique physicochemical properties, including hydrophobic surfaces, high surface area, and susceptibility to aging. Aging processes such as photooxidation, mechanical abrasion, and microbial colonization can significantly alter MP surface chemistry, introducing oxygen-containing functional groups and increasing their adsorption capacity. Heavy metals, in contrast, are non-biodegradable and can accumulate in soils and biota, posing long-term ecological and human health risks through food chain transfer. Pesticides, widely used in modern agriculture, are designed to be biologically active and may persist in soils, affecting non-target organisms and microbial communities.

The coexistence of these pollutants leads to complex interactions that significantly alter their environmental behaviors, including adsorption, desorption, migration, degradation, and toxicity. For example, MPs can act as vectors for heavy metals and pesticides, enhancing their mobility or, conversely, reducing their bioavailability through sorption. These dual effects contribute to uncertainties in environmental risk assessment.

Traditional remediation technologies, such as physical removal and chemical stabilization, are often associated with high cost, low efficiency, and potential secondary pollution. In contrast, microbial remediation has emerged as a promising alternative due to its environmental friendliness, cost-effectiveness, and sustainability. Microorganisms possess diverse metabolic capabilities, enabling them to degrade organic pollutants, transform polymeric materials, and immobilize heavy metals through various biochemical pathways.

This paper reviews the interaction mechanisms of heavy metals, microplastics, and pesticides, as well as recent advances in microbial remediation technologies, aiming to provide theoretical insights and technical support for the management of composite soil pollution.

2. Interaction Mechanisms of Heavy Metals, Microplastics, and Pesticides

2.1. Interaction Between Microplastics and Heavy Metals

Microplastics exhibit strong adsorption capacity for heavy metals through multiple mechanisms, including electrostatic attraction, surface complexation, ion exchange, van der Waals forces, and pore-filling effects[1]. The adsorption behavior is strongly influenced by the physicochemical properties of MPs, such as polymer type (e.g., PE, PP, PET), particle size, crystallinity, and degree of aging.

Aging plays a particularly important role in enhancing metal adsorption. Weathered MPs often possess rougher surfaces and higher oxygen-containing functional groups (e.g., –COOH, –OH), which provide additional binding sites for metal ions. For instance, studies have shown that aged PET microplastics exhibit significantly higher Cd adsorption capacity compared to pristine PE particles due to increased surface polarity and functionalization [2].

Environmental factors such as pH, ionic strength, and the presence of natural organic matter can further influence adsorption–desorption dynamics. Under acidic conditions, competition between H^+ and metal cations may reduce adsorption, while higher pH generally enhances metal binding. However, changes in environmental conditions, especially in biological systems such as the gastrointestinal tract of soil organisms, may trigger desorption of metals from MPs, thereby increasing their bioavailability and toxicity[3-5].

Despite extensive research, the role of MPs in regulating heavy metal bioavailability remains controversial. Some studies suggest that MPs act as "sinks" that immobilize metals and reduce their bioavailability, while others propose that MPs enhance metal transport and exposure through a "vector effect." These discrepancies are largely attributed to differences in experimental conditions, MP characteristics, and metal speciation.

2.2. Interaction Between Microplastics and Pesticides

Microplastics can adsorb pesticides through hydrophobic interactions, hydrogen bonding, and π–π interactions, particularly for aromatic compounds[6,7]. The adsorption capacity is closely related to pesticide hydrophobicity, often represented by the octanol–water partition coefficient (logKow). Compounds with higher logKow values generally exhibit stronger affinity for MP surfaces [8].

Environmental factors, including pH, temperature, and soil composition, significantly influence adsorption–desorption behavior. For example, higher temperatures can enhance molecular diffusion and increase desorption rates, while pH variations may alter pesticide speciation and MP surface charge[9].

In addition to adsorption, MPs can act as carriers, facilitating the long-distance transport of pesticides and increasing their exposure to soil organisms. Experimental studies have demonstrated that the presence of MPs can increase pesticide accumulation in earthworms and induce oxidative stress, indicating enhanced ecological risks[10].

However, MPs may also reduce pesticide bioavailability by sequestering them from the soil solution, thereby decreasing their uptake by organisms. These dual roles highlight the complexity of MP–pesticide interactions. Moreover, pesticides themselves may influence MP aging and microbial colonization, indirectly affecting adsorption behavior and degradation processes.

2.3. Interaction Between Heavy Metals and Pesticides

Heavy metals and pesticides frequently coexist in agricultural soils and interact through complex physicochemical and biological mechanisms. Heavy metals can influence pesticide degradation by catalyzing hydrolysis or redox reactions, while pesticides may alter metal speciation and mobility.

Composite pollution often results in non-additive toxicity effects. Synergistic toxicity may occur when combined pollutants enhance each other's harmful effects, whereas antagonistic interactions may reduce overall toxicity. For example, combined exposure to Cd and certain pesticides has been shown to significantly inhibit plant growth and disrupt physiological processes more severely than single pollutants [11].

In addition to plant toxicity, composite pollution can affect soil microbial communities by altering enzyme activities, metabolic functions, and community structure [12,13]. These changes may further influence nutrient cycling and ecosystem stability. However, the underlying mechanisms governing these interactions remain poorly understood and require further investigation, particularly at the molecular and microbial community levels.

3. Advances in Microbial Remediation Technologies

3.1. Microbial Degradation of Microplastics

Microbial degradation of MPs has attracted increasing attention as a sustainable approach to plastic pollution. Both bacteria and fungi have demonstrated the ability to degrade various polymers, including polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET) [14].

The degradation process typically involves several stages: biodeterioration, fragmentation, assimilation, and mineralization. During biodeterioration, microbial colonization alters the physical and chemical properties of MPs. Enzymes such as laccases, esterases, and oxygenases play critical roles in polymer breakdown[15-17].

Fungi are particularly effective due to their filamentous growth and ability to secrete extracellular enzymes. In addition, symbiotic systems, such as insect gut microbiota, have been reported to enhance plastic degradation efficiency, suggesting potential applications in engineered systems [18].

3.2. Microbial Immobilization of Heavy Metals

Microorganisms can immobilize heavy metals through mechanisms such as biosorption, bioaccumulation, precipitation, and redox transformation [19]. Functional groups on microbial cell walls, including carboxyl, hydroxyl, and amino groups, can bind metal ions through complexation and ion exchange.

Extracellular polymeric substances (EPS) also play an important role by providing additional binding sites and forming protective barriers. Certain bacteria, such as *Pseudomonas* and *Bacillus*, exhibit strong metal-binding capacities and are widely used in bioremediation studies[20].

Microbial metabolism can induce the formation of insoluble metal precipitates, thereby reducing metal mobility and toxicity. For example, sulfate-reducing bacteria can convert soluble metal ions into metal sulfides, which are less bioavailable[21,22].

3.3. Microbial Degradation of Pesticides

Microbial degradation is a key pathway for pesticide removal in soils. Microorganisms degrade pesticides through enzymatic reactions involving monooxygenases, dioxygenases, and hydrolases [23,24]. These enzymes catalyze the breakdown of complex organic molecules into simpler, less toxic compounds.

Microbial consortia often exhibit higher degradation efficiency than single strains due to synergistic metabolic interactions. Different microorganisms can cooperate to degrade intermediate products, enhancing overall degradation rates [25,26]. Environmental factors such as temperature, pH, and nutrient availability significantly influence microbial activity and degradation efficiency.

3.4. Microbial Remediation of Composite Pollution

Microbial remediation of composite pollution involves the simultaneous degradation of MPs and pesticides and immobilization of heavy metals. However, the coexistence of multiple pollutants may inhibit microbial activity due to toxic effects and environmental stress.

Plant–microbe combined remediation has emerged as an effective strategy for addressing these challenges. In the rhizosphere, plant roots exude organic compounds that stimulate microbial activity, while microorganisms enhance plant growth and pollutant removal through nutrient mobilization and stress alleviation.

Despite its potential, research on microbial remediation of heavy metal–microplastic–pesticide composite pollution is still in its early stages. Key challenges include maintaining microbial stability under complex environmental conditions and optimizing interactions among different functional microorganisms.

4. Conclusion and Perspectives

This review highlights the complex interactions among heavy metals, microplastics, and pesticides in soil environments. Microplastics play dual roles as both carriers and regulators of pollutant behavior, influencing the migration, transformation, and bioavailability of coexisting contaminants. Meanwhile, microbial remediation technologies offer promising solutions for mitigating composite pollution due to their versatility and sustainability.

However, current research mainly focuses on single or binary pollutant systems, and studies on multi-pollutant interactions remain limited. Future research should prioritize: (i) elucidating the mechanisms of multi-pollutant interactions at molecular and microbial community levels; (ii) developing robust microbial consortia capable of functioning under complex environmental stress; and (iii) integrating microbial technologies with other remediation strategies for field-scale applications.

Overall, advancing our understanding of composite pollution and developing efficient remediation strategies are essential for ensuring soil health and sustainable agricultural development.

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