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Temporal Fate and Transformation of Copper and Lead Nanoparticles in Sewage Sludge-Amended Soils: Implications for Environmental Impact

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The increasing use of engineered nanoparticles (ENPs) in industrial and consumer applications has led to their accumulation in sewage sludge, raising critical concerns about their fate and environmental impact when biosolids are applied to agricultural soils. Despite growing awareness, current regulatory frameworks for biosolids application rely only on total metal concentrations, failing to account for nanoparticle dynamics such as dissolution kinetics, aggregation behavior, and mineralogical transformations that fundamentally determine bioavailability and ecological risk.

This study investigated the fate and transformation of copper (Cu) and lead (Pb) NPs in sewage sludge-amended soils over a 60-day incubation experiment, using single particle inductively coupled plasma mass spectrometry (sp-ICP-MS) to simultaneously characterize particle mass concentration, particle number concentration, mean particle size, and total metal concentration across sixteen treatment combinations (acidic vs. alkaline soils; 5% vs. 20% sludge loading; TSPP vs. Milli-Q extraction).

Results showed that the fate of nanoparticles in sludge-amended soils is governed by a time-dependent interplay of physical, chemical, and soil-specific processes. In the initial period, physical disaggregation was the dominant process, creating a critical window of maximum particle mobility regardless of soil type or amendment rate. As incubation continued, soil chemistry increasingly influenced metal transformation pathways, with pH and organic matter content driving different aggregation, precipitation, and dissolution processes for Cu and Pb NPs. In later stages, soil type became the primary factor, with acidic soils presenting persistent remobilization risk while alkaline soils, particularly for Pb NPs, achieved progressive stabilization through transformation to stable mineral phases, demonstrating that soil conditions can fundamentally determine whether nanoparticles persist as mobile, bioavailable species or become effectively immobilized over time.

These findings advance the understanding of ENP fate in soil-sludge systems, with broader implications for environmental risk assessment under future climate scenarios, where climate-driven soil acidification may significantly alter ENP speciation, mobility, and bioavailability in sludge-amended soils.

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