# Exploring the single and combined effects of ZnO nanoparticles and cadmium on soil parameters

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Keywords: ZnO nanoparticles, cadmium, soil physicochemical properties, nanophytoremediation.
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Heavy metal contamination is widely recognized as a critical environmental problem due to the high toxicity, persistence and bioaccumulation of these elements in soil–plant systems, posing long-term risks to soil quality, ecosystem functioning, and agricultural sustainability (Rai et al., 2019; Ali et al., 2019). Among heavy metals, cadmium (Cd) is of particular concern because of its high mobility in soils and efficient transfer to plants, which can lead to ecological degradation and reduced soil productivity (Du et al., 2021). Elevated Cd concentrations disrupt soil properties and biological processes, limiting plant growth. Development of remediation technologies that reduce environmental risk while preserving soil quality is therefore critical. Phytoremediation using energy crops has emerged as a sustainable, environmentally friendly approach to manage contaminated soils, enabling the productive use of degraded land without competing with food production (Hauptvogl et al., 2020; Nedjimi, 2021). Energy crops are particularly suitable for phytoremediation due to their high biomass production, tolerance to stress conditions and ability to influence rhizosphere processes such as soil aeration, moisture dynamics and organic matter turnover (Bortoloti and Baron, 2022). Advances in nanotechnology have further expanded the potential of phytoremediation through the development of nanophytoremediation strategies that combine plants with engineered nanoparticles to enhance stress tolerance and remediation efficiency (Gomes, 2025; Chen et al., 2025; Sol-Magdaleno et al., 2025). Zinc oxide (ZnO) nanoparticles have received considerable attention in this context due to their capacity to mitigate Cd-induced phytotoxicity, regulate antioxidant defence systems and modify soil–plant interactions (Gao et al., 2022; Umair Hassan et al., 2024; Chen et al., 2024). However, despite growing interest in nanoparticle-assisted phytoremediation, most studies have focused on plant physiological responses, while implications for soil quality indicators remain underexplored.

The aim of this study was to evaluate the effects of ZnO nanoparticles on soil quality during the nanophytoremediation of Cd-contaminated soil using the energy crop *Brassica juncea*. During the experiment, plants were grown in pots within growth chambers under controlled conditions at 21 °C. Soils were spiked with Cd at 0, 1, 10, 50, and 100 mg kg$^{-1}$ and amended with ZnO nanoparticles (0 or 0.2 g kg$^{-1}$). Soil temperature, moisture, organic matter (SOM) content, carbon dioxide, oxygen, pH, and electrical conductivity were monitored to assess changes in soil physicochemical properties.

Results showed that these factors responded differently across the Cd contamination gradient and ZnO treatments, suggesting that ZnO nanoparticles modulate Cd-induced effects on soil parameters. Electrical conductivity (EC) responded non-linearly to Cd, decreasing by 7.8% at 1 mg kg$^{-1}$ but increasing by 15.2% at 10 mg kg$^{-1}$. These contrasting trends likely reflect concentration-dependent changes in soil ionic composition, affecting nutrient availability, ion sorption, and rhizosphere activity. Such non-linear patterns emphasize that the level of contamination strongly shapes soil responses during phytoremediation.

Soil temperature increased modestly (1.6–4.7%), likely reflecting enhanced microbial activity. Soil pH also rose in nearly all treatments by 1.3–3.4%, suggesting a shift toward less acidic conditions. This shift could reduce Cd solubility and toxicity while reflecting interactions between plant activity and ZnO nanoparticles with soil buffering processes.

Soil organic matter content increased in all treatments by 4.4–34.3%, indicating an overall improvement in soil quality. This enrichment likely stems from root biomass, exudates, and microbial residues during plant growth, which collectively enhance nutrient cycling, soil structure, and contaminant immobilization. Because SOM plays a important role in nutrient cycling, soil structure, and contaminant binding, its enrichment is a positive outcome for sustainable soil phytoremediation.

Dynamic changes in soil gases reflected increased biological activity: oxygen decreased by 0.6–4.8%, while carbon dioxide increased by up to 42.4%, consistent with intensified microbial respiration in the rhizosphere under Cd contamination. Soil moisture also increased by 3.1–15.6% in most treatments, suggesting improved water retention, likely supported by higher SOM content and changes in soil structure.

ZnO nanoparticle-assisted phytoremediation with *Brassica juncea* improved soil quality and boosted biological activity, including nutrient cycling, organic matter accumulation, and microbial respiration. Beyond supporting plant growth, the treatment clearly influenced soil chemistry and biological function, highlighting the interconnected responses of soil and plants during remediation. These findings emphasize that evaluating nanoparticle-assisted strategies requires looking at both plant performance and soil health. By enhancing soil structure, chemistry, and biological activity, this approach shows promise for restoring long-term soil health and supporting resilient ecosystems.

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