Zinc Oxide Nanoparticle Impact to Phytoremediation of Cd-Contaminated Soil Using Brown Mustard (*Brassica juncea* L.)

Inesa Kniuipytė[1], Inesa Sinkevičiūtė[1], Aušra Sinkevičienė[2], Rasa Kimbirauskienė[2], Marius Praspaliauskas[1]

[1]Laboratory of Heat Equipment Research and Testing, Lithuanian Energy Institute, Breslaujos 3, LT44404 Kaunas, Lithuania

[2]Department of Agroecosystems and Soil Sciences, Agriculture Academy, Vytautas Magnus University, Studentų str. 11, LT-53361, Akademija, Kaunas district, Lithuania

Keywords: *Brassica juncea*, Nano-phytoremediation, ZnO NPs, Heavy metal, Cd contamination.

E-mail contact: inesa.kniuipyte@lei.lt

Abstract

Persistent soil contamination with heavy metals (HM) remains a critical environmental concern due to their persistence, bioaccumulation, and negative impacts on surrounding ecosystems (Hadia-e-Fatima and Ahmed, 2018; Khalef et al., 2022). According to the United States Environmental Protection Agency (US EPA), soil contamination with heavy metals has already contributed to health problems in an estimated 10 million people worldwide, demonstrating that HM pollution poses a critical threat not only to ecosystem integrity but also to human health (O'Connor et al., 2019). Cadmium (Cd) was selected as the target contaminant because of its high mobility, bioavailability, and pronounced toxicity even at low concentrations, making it one of the most hazardous and strictly regulated heavy metals (Ali et al., 2020; Haider et al., 2021).

Phytoremediation has emerged as a sustainable strategy for mitigating HM contamination, but its efficiency is often constrained by the growth-inhibiting and stress-inducing effects of metals on plants. In parallel, engineered nanomaterials—particularly zinc-based nanoparticles (ZnO NPs)—offer new opportunities to enhance nutrient availability, strengthen plant stress tolerance, and stimulate biomass accumulation (Hassan et al., 2024). Their unique reactivity has attracted considerable attention as soil amendments capable of supporting phytoremediation processes. However, nano-assisted phytoremediation is still at an early stage, with critical gaps remaining in our understanding of nanoparticle–metal interactions, mixture effects, and the optimization of safe and effective dosages (Verma et al., 2021; Prakash and Chandran, 2023; Ningombam et al., 2024). Addressing these knowledge gaps is essential for advancing environmentally responsible, nano-enabled strategies that improve plant performance while safeguarding ecosystem health.

In this work, we investigated how zinc oxide nanoparticles (ZnO NPs) applied at 0, 200, and 300 mg kg^{-1} influence the growth and physiological performance of Brown mustard (*Brassica juncea* L.) cultivated in cadmium-contaminated soils (0–50 mg kg^{-1} Cd) under controlled environmental conditions (21/14 °C day/night, 400 ppm CO_2, 55–70% relative humidity). Plant responses were quantified through multiple functional traits—including chlorophyll content, shoot height, root length, and shoot and root dry biomass, plant tolerance to contamination—that collectively reflect both stress intensity and the plant's phytoremediation capacity.

Cadmium exposure caused a clear, concentration-dependent decline across all measured growth parameters, demonstrating the strong phytotoxic pressure imposed by the Cd. However, the introduction of ZnO NPs—particularly at lower doses—partially counteracted Cd-induced stress. Treated plants exhibited higher chlorophyll retention, improved root development, and increased above- and below-ground biomass compared to Cd-only controls. The most pronounced positive effects were observed at 1–10 mg kg^{-1} Cd, likely due to Zn functioning as an essential micronutrient and moderating Cd's inhibitory effects. At elevated Cd levels (≥50 mg kg^{-1}), ZnO NP amendments still provided some mitigation, though not sufficient to fully overcome the toxicity. Notably, the higher nanoparticle dose (300 mg kg^{-1}) occasionally exacerbated stress symptoms, suggesting a threshold beyond which ZnO NPs may shift from beneficial to detrimental.

Altogether, these findings demonstrate that modest applications of ZnO NPs can modulate plant stress physiology, promote biomass production, and enhance cadmium uptake—ultimately improving phytoremediation efficiency in contaminated soils. The results offer new insight into nanoparticle–metal interactions in complex soil systems and highlight both the potential and the necessity of careful dose optimization when integrating nanomaterials into sustainable, nano-enabled phytoremediation strategies for environmental risk management.

References

1. O'Connor D, Hou D, Ok YS, Mulder J, Duan L, Wu Q, Wang S, Tack FMG, Rinklebe J. Mercury speciation, transformation, and transportation in soils, atmospheric flux, and implications for risk management: a critical review. Environ Int. 2019;129:747–761.
2. Ali E, Hussain A, Ullah I, Khan FS, Kausar S, Rashid SA, Rabbani I, Imran M, Kakar KU, Shah JM, Cai M, Jiang L, Hussain N, Sun P. Cadmium phytotoxicity: issues, progress, environmental concerns and future perspectives. Rev la Fac Cienc Agrar. 2020;52(1):391–405.
3. Khalef RN, Hassan AI, Saleh HM. Heavy metal's environmental impact. In: Environmental Impact and Remediation of Heavy Metals. 2022.
4. Hadia-e-Fatima A, Ahmed A. Heavy metal pollution – a mini review. J Bacteriol Mycol. 2018;6(3):179–181.
5. Prakash P, Chandran SS. Nano-phytoremediation of heavy metals from soil: a critical review. Pollutants. 2023;3:360–380.
6. Hassan MU, Huang G, Haider FU, Khan TA, Noor MA, Luo F, Zhou Q, Yang B, Ul Haq MI, Iqbal MM. Application of zinc oxide nanoparticles to mitigate cadmium toxicity: mechanisms and future prospects. Plants (Basel). 2024;13(12):1706. https://doi.org/10.3390/plants13121706
7. Haider FU, Cai L, Coulter JA, Cheema SA, Wu J, Zhang R, Wenjun M, Farooq M. Cadmium toxicity in plants: impacts and remediation strategies. Ecotoxicol Environ Saf. 2021;211:111887. https://doi.org/10.1016/j.ecoenv.2020.111887
8. Ningombam L, Mana T, Apum G, Ningthoujam R, Disco Singh Y. Nano-bioremediation: a prospective approach for environmental decontamination in soil, water and heavy metals. Environ Nanotechnol Monit Manage. 2024;21:100931. https://doi.org/10.1016/j.enmm.2024.100931
9. Verma A, Roy A, Bharadvaja N. Remediation of heavy metals using nanophytoremediation. In: Shah MP, editor. Advanced Oxidation Processes for Effluent Treatment Plants. Elsevier; 2021. p. 273–296. https://doi.org/10.1016/B978-0-12-821011-6.00013-X