Exploring the Single and Combined Effects of ZnO Nanoparticles and Cadmium on Soil Parameters

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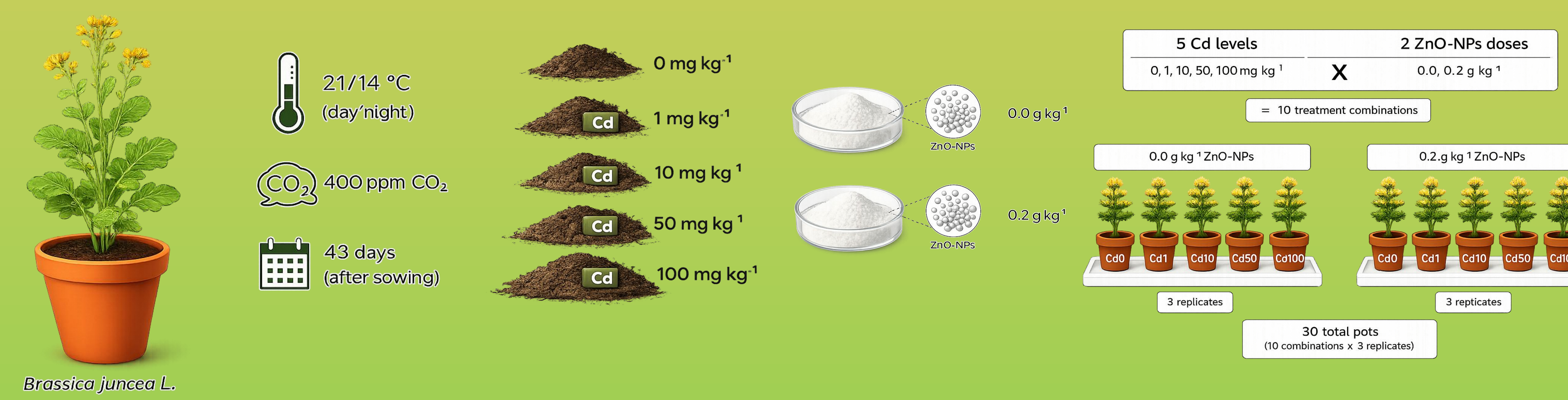
Introduction

Heavy metal contamination, particularly with cadmium (Cd), poses a serious threat to soil quality and agricultural sustainability due to its toxicity and high mobility in the environment. Phytoremediation using energy crops has emerged as a sustainable strategy for the management of contaminated soils. In recent years, increasing attention has been given to nanophytoremediation approaches, especially the application of zinc oxide nanoparticles (ZnO-NPs), which have the potential to enhance remediation efficiency and improve plant tolerance to environmental stress. Nevertheless, their impact on soil quality and ecological safety remains insufficiently understood. Therefore, the aim of this study was to evaluate the combined effects of cadmium (Cd) contamination and ZnO nanoparticles on soil physicochemical and biological properties relevant to phytoremediation efficiency and ecological safety.

Methods

A pot experiment was conducted to evaluate the effects of ZnO-NPs on soil quality during nanophytoremediation of Cd-contaminated soil using *Brassica juncea* L. Plants were grown under controlled conditions. Soils were spiked with Cd (0-100 mg kg^{-1}) and treated with ZnO-NPs. After plant biomass harvest, soil physicochemical properties were analyzed. . Soil CO_2 and O_2 concentrations were measured using a SCREENALYT gas analyzer (Honold Umweltmesstechnik, Germany). Soil moisture, temperature, and electrical conductivity were determined using an HH_2 Moisture Meter (Delta-T Devices Ltd., Cambridge, UK), while soil pH was measured using a Hanna pH meter. Soil organic matter (SOM) was determined using the loss on ignition (LOI) method. Statistical analysis was performed using SYSTAT 10 software for comparison of treatment means, with significance levels set at $p \le 0.05$, $p \le 0.01$, and $p \le 0.001$. Factorial ANOVA was conducted using Statistica software to evaluate the effects of Cd concentration, ZnO-NPs dose, and their interactions on the investigated parameters.



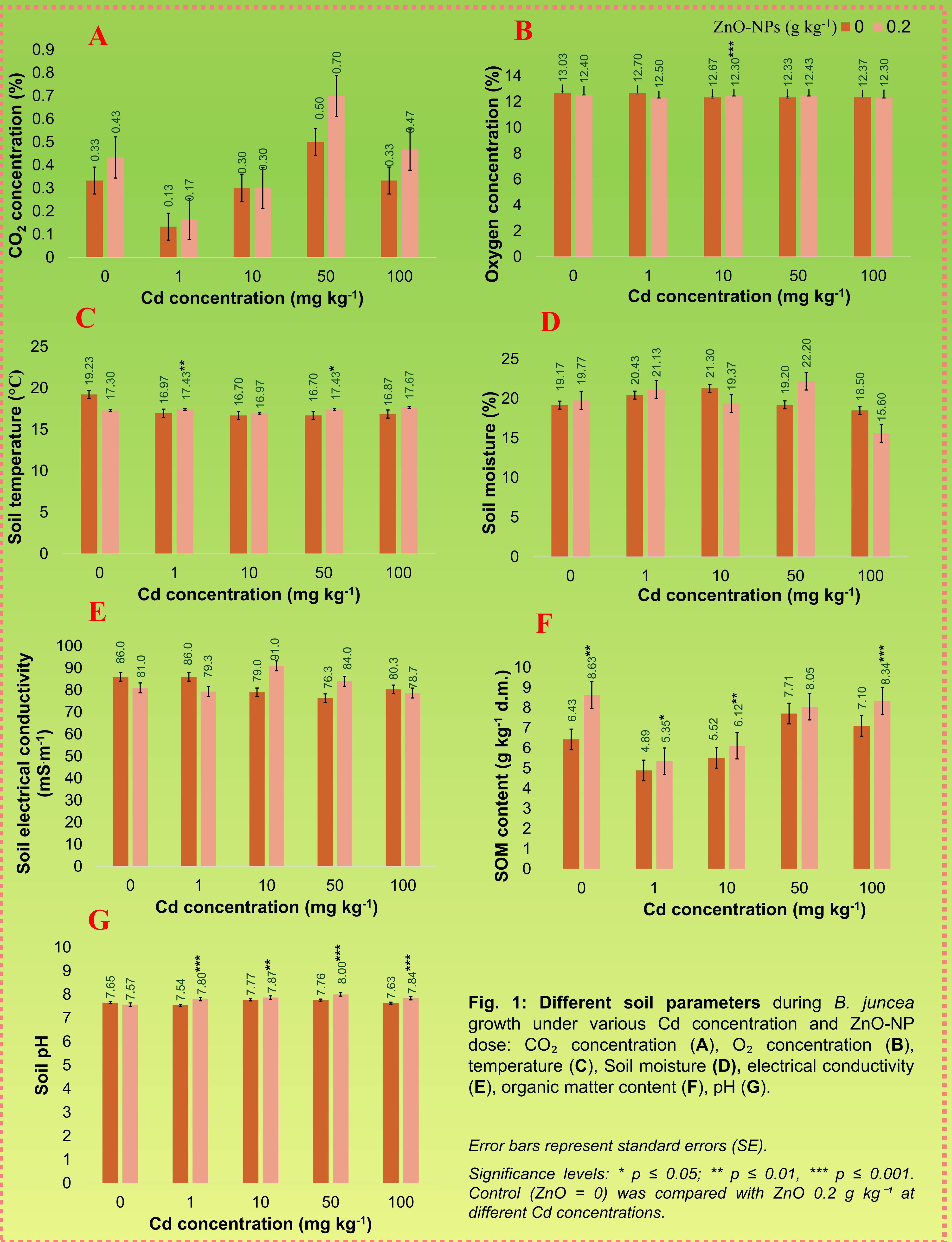


Fig. 1: Different soil parameters during *B. juncea* growth under various Cd concentration and ZnO-NP dose: CO_2 concentration (**A**), O_2 concentration (**B**), temperature (**C**), Soil moisture (**D**), electrical conductivity (**E**), organic matter content (**F**), pH (**G**).

Error bars represent standard errors (SE).

*Significance levels: * $p \le 0.05$; ** $p \le 0.01$, *** $p \le 0.001$. Control (ZnO = 0) was compared with ZnO 0.2 g kg^{-1} at different Cd concentrations.*

Results & Discussion

- CO_2 levels increased (up to 40.2 %), indicating intensified microbial respiration in the rhizosphere (Fig. 1A.). O_2 concentration showed a variable response across Cd treatments, increasing at the control (4.9 %) and at 50 mg kg^{-1} (0.8 %), while decreasing at 1 mg kg^{-1} (1.6 %), 10 mg kg^{-1} (2.9 %), and 100 mg kg^{-1} (0.5 %), indicating a non-linear response to increasing Cd levels (Fig. 1B.). Soil temperature decreased at 0 mg kg^{-1} Cd (10.0 %) but increased at all other Cd levels (1.6–4.7 %), showing a gradual increase as Cd concentration increased (Fig. 1C.).
- Soil moisture increased at 0 mg kg^{-1} (3.1 %), 1 mg kg^{-1} (3.4 %), and 50 mg kg^{-1} (15.6 %) Cd, but decreased at 10 (9.1 %) and 100 mg kg^{-1} (15.7 %), indicating a variable, non-linear response across Cd concentrations (Fig. 1D.). EC decreased at 0 mg kg^{-1} (5.8 %), 1 mg kg^{-1} (7.8 %), and 100 mg kg^{-1} (2.1 %) Cd, but increased at 10 mg kg^{-1} (15.2 %) and 50 mg kg^{-1} (10.0 %), indicating a non-linear response to Cd concentration and changes in soil ionic composition (Fig. 1E.). SOM increased in all Cd treatments (4.4–34.3 %), with the highest rise at 0 mg kg^{-1} (34.3 %) (Fig. 1F.). The increase was substantial in nearly all cases, indicating a consistent and significant improvement in soil organic matter across treatments. Soil pH decreased at 0 mg kg^{-1} Cd (1.0 %) but increased at all other Cd levels (1.3 –3.4 %), with all increases being statistically significant, indicating a consistent shift toward less acidic conditions under combined Cd and ZnO nanoparticle treatments (Fig. 1G.).

- Cd soil concentration significantly affected soil CO_2 concentration, soil O_2 concentration, soil moisture, soil pH, and SOM, indicating that Cd contamination altered soil respiration, physicochemical conditions, and organic matter dynamics (Table 1).
- ZnO-NPs significantly affected soil O_2 concentration, soil moisture, soil pH, and SOM, demonstrating that nanoparticle amendments modified soil biological activity and physicochemical properties.
- Significant Cd × ZnO-NPs interaction effects were observed for soil O_2 concentration, soil pH, and SOM, indicating that nanoparticle impacts on soil functioning depended on Cd contamination level.

Table 1. Significance levels (factorial ANOVA) of soil CO_2 and O_2 concentrations, moisture, temperature, EC, and pH during *B. juncea* growth under various Cd concentrations in soil and ZnO-NP doses. ns > 0.05

	Factors		
	Cd	NPs ZnO	Cd x NPs ZnO
CO_2 conc.	$p < 0.001$	ns	ns
O_2 conc.	$p < 0.05$	$p < 0.05$	$p < 0.05$
Moisture content	ns	ns	ns
Temperature	$p < 0.05$	ns	$p < 0.05$
Electrical Conductivity	ns	ns	ns
pH	$p < 0.001$	$p < 0.001$	$p < 0.001$
Organic matter content	$p < 0.001$	$p < 0.001$	$p < 0.05$

Conclusions

- ✓ Moderate doses of ZnO-NPs stimulated soil biological activity even under Cd stress conditions.
- ✓ Significant interactions between ZnO-NPs and Cd concentrations affected soil O_2, temperature, pH, and SOM, showing that nanoparticle effects depend on contamination level and modify the soil biochemical response to Cd stress.
- ✓ ZnO nanoparticle-assisted phytoremediation with Brassica juncea improved soil quality and soil–plant interactions at controlled doses, whereas excessive ZnO-NPs or higher Cd concentrations may negatively affect soil functioning and ecological stability.

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