Climate-Modulated Cadmium Phytoremediation: Biomass, Uptake, and Removal Efficiency of *Brassica napus*

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Abstract

Soil contamination with cadmium (Cd) remains a pressing environmental issue due to its toxicity, persistence, and the growing influence of anthropogenic activities—such as mining, smelting, wastewater and sludge application, and intensive agrochemical use—which have markedly increased its spread across industrial, agricultural, and urban landscapes. Cadmium (Cd) is among the most dangerous non-essential heavy metals due to its extreme phytotoxicity even at trace concentrations, severely impairing plant growth and photosynthetic function. Although natural Cd levels in soils are typically low (0.01–1 mg kg^{-1}), concentrations above 3 mg kg^{-1} are considered critically polluted, and anthropogenic activities often raise levels far beyond this threshold (Dutta et al., 2021; Haider et al., 2021). Its persistence, high mobility, and rapid plant uptake make Cd a major ecological and agricultural threat.

Effective remediation through phytoextraction is therefore crucial, as it removes Cd from soils without allowing it to enter the food chain or spread to surrounding areas, and when energy crops are used, the harvested contaminated biomass can be safely converted into bioenergy (Yan et al., 2020; Dutta et al., 2021; Haider et al., 2021; Khan et al., 2021). Phytoremediation using fast-growing, high-biomass crops offers a sustainable solution, yet its efficiency is strongly influenced by environmental factors, including soil water content (SWC), temperature, and atmospheric CO_2 concentration, all of which are expected to change under ongoing climate change (IPCC et al., 2022; Dikšaitytė et al., 2019). Oilseed rape (*Brassica napus* L.), with its high growth rate, biomass yield, and tolerance to Cd, elevated temperature, and CO_2, represents a promising candidate for phytoremediation and concomitant bioenergy production.

This study evaluated the individual and combined effects of SWC (optimal 30 %, reduced 10 %, elevated 40 %), temperature (ambient 21/14 °C, elevated 25/18 °C), and elevated CO_2 (400 vs. 800 ppm) on the growth, Cd accumulation, and phytoremediation potential of *B. napus* in soils spiked with 0–50 mg kg^{-1} Cd. A total of 108 pots were prepared, each filled with 2.5 kg of soil mixtures at the designated Cd concentrations, with all treatments established in triplicate. Throughout the experiment, plants were irrigated with tap water to maintain an initial optimal SWC of 30 %, while the reduced and elevated SWC treatments were applied during the final 18 days of growth. At harvest (9 weeks after sowing), shoot height, root length, fresh and dry biomass were measured. Cadmium concentrations in roots and shoots were determined, and plant performance was evaluated using the tolerance index (TI), bioconcentration factor (BCF), translocation factor (TF), and Cd removal efficiency. This experimental design enabled a robust evaluation of how key climate-related environmental factors modulate plant development, Cd accumulation patterns, and the overall effectiveness of phytoextraction under controlled and reproducible conditions.

Cadmium exposure significantly reduced plant biomass and TI in a concentration-dependent manner, particularly at 50 mg kg^{-1}, while moderate Cd contamination (1–10 mg kg^{-1}) had limited negative effects. Elevated temperature and combined elevated temperature with CO_2 enhanced plant biomass and mitigated Cd toxicity, with the greatest improvements observed under optimal and elevated SWC. Cd primarily accumulated in roots, with shoot Cd content and overall Cd removal strongly influenced by environmental conditions. BCF values exceeded 1 in most treatments, indicating effective Cd uptake, while TF was generally <1 under high SWC, suggesting restricted root-to-shoot translocation. The highest Cd removal rates were achieved under ETC conditions, particularly at low to moderate soil Cd concentrations and optimal SWC, reducing the theoretical number of harvest cycles required for remediation. Bioenergy potential, estimated from shoot biomass, was negatively correlated with soil Cd concentration but enhanced by elevated temperature and CO_2 under optimal and elevated SWC.

Our findings show that *Brassica napus* is a strong candidate for restoring Cd-contaminated soils, even under shifting climate conditions. Optimal soil moisture remained the key driver of successful phytoremediation,

enabling high biomass production and efficient Cd removal. While elevated temperature and CO_2 further enhanced plant growth and metal uptake, these benefits were strongly modulated by water availability. Thus, effective phytoremediation strategies under climate change must integrate careful moisture management to maintain plant performance and maximize both remediation efficiency and bioenergy potential.

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