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Nanotechnology-Assisted Phytoremediation: A Hybrid Strategy for Superior Contaminant Removal

Shamiran Salih Abdulrahman[1,2], Muhammad Yasir Naeem[3*], Dilara K. Sunakbaeva[4], Yaira Rakhmetova[5], Abdol Ghaffar Ebadi[6]

[1]Biology Research Center, Faculty of Science, University of Zakho, Zakho, Iraq
[2]Department of Biology, Faculty of Science, University of Zakho, Zakho, Iraq
[3]Department of Agronomy, Animals, Food, Natural Resources and the Environment (DAFNAE), University of Padua, Italy
[4]Faculty of Sciences, Department of Ecology and Chemistry, Khoja Akhmet Yassawi International Kazakh-Turkish University, Turkestan, Kazakhstan
[5]Department of Biotechnology, Faculty of Biology and Biotechnology, Al Farabi Kazakh National University, Almaty, Kazakhstan
[6]Researcher and Faculty member, Jouybar branch, Islamic Azad University, Jouybar, Iran
*Presenter Author's Email: yasir.naeem91@yahoo.com

Abstract

Nanotechnology is revolutionizing phytoremediation by enhancing plant-microbe interaction, pollutant bioavailability, and detoxification mechanisms. This review examines the synergistic potential of combining nanoparticles with plants for promoting the uptake and degradation of heavy metals, pesticides, and organic pollutants. Engineered nanoparticles such as nano-iron, nano-TiO_2, and carbon-based nanomaterials are shown to trigger root exudates, enhance enzyme activities, and modulate redox conditions in the rhizosphere. The review also discusses nanoparticle-mediated delivery systems for plant growth regulators and microbial inoculants. Problems of nanoparticle toxicity, persistence, and ecotoxicological impacts are viewed critically. Case studies demonstrate the effectiveness of nanotechnology-enhanced systems over classical phytoremediation systems in contaminated soils, water, and sediments. This combinatorial concept opens new fields in environmental nanobiotechnology and offers promise for real-time site-specific remediation with improved efficacy and control.

Keywords: Nanotechnology, Nanoparticles, Hybrid phytoremediation, Nano-iron, Environmental nanobiotech, Plant-nano interactions