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Beyond Green Barriers: Genetic Engineering Progress toward Enhanced Phytoremediation Efficiency

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Abstract
Phytoremediation has been acknowledged as an environment-friendly and cost-effective method for avoiding environmental contamination, particularly in contaminated soil and water. However, the plant uptake capacity limit and stress resistance limit prevent its large-scale application as a green technology. Current advances in genetic engineering offer promising answers to overcome these limitations through enhanced metal uptake, detoxification processes, and biomass yield. This review compiles the latest breakthroughs in molecular engineering, including CRISPR/Cas-mediated genome editing, overexpression of metal transporter genes, and transgenic insertion of antioxidant pathways. Omics tools such as transcriptomics, proteomics, and metabolomics have expedited the identification of novel gene targets associated with hyperaccumulation and resistance. Furthermore, synthetic biology is also enabling the development of modular genetic circuits to control phytoremediation reactions under different environmental conditions. The review also examines biosafety concerns, ecological impact, and regulation of genetically engineered phytoremediators. Overall, biotechnology application in phytoremediation not only increases its potential for remediation of the environment but also results in the development of circular and robust biotechnologies towards sustainable development across the globe.

Keywords: Genetic engineering, Phytoremediation, CRISPR/Cas9, Hyperaccumulators, Molecular biology, Transgenic plants