

Engineered Nanomaterials for Water and Soil Remediation: A Review of Synthesis, Mechanisms, and Applications

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Abstract

Contamination of water and soil by heavy metals, synthetic dyes, pharmaceutical residues, and pesticide residues remains a persistent environmental problem that continues to demand improved remediation tools. This review examines engineered nanomaterials as a versatile remediation platform spanning carbon based materials, nanoscale zero valent iron (nZVI), metal organic frameworks (MOFs), zeolite and clay nanocomposites, and two dimensional materials such as MXenes and layered double hydroxides (LDHs). The value of these materials lies not only in their high surface area to volume ratio but also in the precision with which their surface chemistry can be tuned by doping, functionalisation, or hybridisation to target specific pollutants. Literature published between 1958 and 2024 was screened to compare the synthesis of each class, the mechanisms by which they operate, and their reported performance. Adsorption is the dominant pathway in most classes, operating through electrostatic attraction, π - π stacking, surface complexation, and ion exchange, whereas nZVI relies on reductive electron transfer and MXenes and semiconductor hybrids contribute a catalytic dimension. Reported removal efficiencies frequently exceed 90 to 99 per cent for heavy metals and dyes, with certain MOF adsorbents exceeding 1,000 mg g⁻¹ and MXene systems surpassing 95 per cent heavy metal removal. In soil, amendments based on biochar, zeolite, and iron nanoparticles immobilise heavy metals and accelerate the breakdown of persistent pesticides. A comparative assessment indicates an approximately inverse relationship between reported laboratory capacity and practical deployability, which is identified here as the central obstacle to field adoption.

Keywords

Adsorption, engineered nanomaterials, heavy metals, nanoscale zero valent iron, soil remediation, water remediation.