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Pollution to Solution: Nano-Enabled Strategies in Wastewater Treatment and Resource Recovery

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Abstract
Nanotechnology has been a breakthrough technology in wastewater treatment and resource recovery because it possesses high surface area, reactivity, and selectivity in adsorption. This review discusses the most recent nano-enabled methods for the removal of contaminants including heavy metals, pharmaceuticals, pathogens, and microplastics from industrial and domestic wastewater. Nanomaterials such as carbon nanotubes, graphene oxide, metal-organic frameworks (MOFs), and magnetic nanoparticles are emphasized in the context of action mechanism, regeneration ability, and environmental safety. Hybrid systems that incorporate nanomaterials with membrane filtration, photocatalysis, and electrochemical treatment for optimal use are discussed in the article. Special consideration is given to the recovery of useful resources like nutrients and rare earth elements during treatment. Environmental risk assessment, regulatory barriers, and lifecycle concerns are also addressed to achieve responsible deployment and development of nano-based technology. This review concludes by proposing future directions such as green synthesis, AI-driven nano-design, and decentralized nano-filtration units for smart and sustainable wastewater management.

Keywords: Nanotechnology, Wastewater treatment, Nanomaterials, Resource recovery, Water purification, Environmental safety