Advanced Graphene-Integrated Hybrid Adsorption System for High-Efficiency Industrial and Domestic Wastewater Treatment

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Abstract
The rapid and uncontrolled discharge of untreated industrial effluents and domestic wastewater has intensified global water pollution, emerging as one of the most critical environmental challenges of this decade. Elevated concentrations of total dissolved solids (TDS), toxic heavy metals, and complex organic contaminants severely degrade aquatic ecosystems and pose severe health risks to humans. While conventional approaches such as sand filtration and activated carbon are widely adopted, their performance is often limited by inadequate adsorption capacity, low durability, and restricted reusability—making them unsuitable for long-term, large-scale deployment. This study introduces a graphene-based hybrid adsorption technology engineered to overcome these limitations and achieve high-efficiency pollutant removal. The system integrates multiple graphene-enhanced materials to form a robust and high-surface-area adsorption matrix. Expanded graphite acts as the structural backbone, while graphene-coated sand significantly enhances the adsorption capability of traditional filter media. Graphene-coated zeolite further improves ion-exchange behavior and adsorption selectivity. Additionally, graphene oxide-derived reduced graphene (rGO) provides abundant functional groups enabling efficient bonding with dissolved ions, organic pollutants, and heavy metals. A final activated charcoal polishing layer ensures the removal of trace contaminants, leading to superior purification. Laboratory-scale experiments were performed using both synthetic and real wastewater samples across a range of operating conditions. The proposed system consistently outperformed conventional treatment units, achieving 90–95% removal efficiency for TDS, heavy metals, and organic pollutants. The hybrid composite materials demonstrated excellent structural stability and retained high performance over multiple regeneration cycles. Overall, the findings confirm the potential of graphene-based composite adsorbents as a cost-effective, scalable, and sustainable solution for wastewater treatment. The proposed system offers a promising pathway toward next-generation purification technologies suitable for industrial deployment and high-volume domestic applications.