Unveiling the removal performance of banana peel biochar and rice husk nanoparticles for crystal violet and methylene blue dyes from aqueous media

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The discharge of dye-laden effluents, particularly dark-colored dyes like Crystal violet (CV) and Methylene blue (MB), presents substantial environmental challenges due to their proved toxicity and environmental persistence. This inves tigation evaluates the efficacy of functionalized agricultural byproducts—rice husk nanoparticles (RHNPs) and banana peel biochar (BPBC)—as sustainable adsorbents for dye sequestration from aqueous media under various application conditions. Comprehensive characterization via DLS, FTIR, XRD, TGA, SEM, and AFM revealing several functions such as –OH and –COOH and monodisperse nanoparticles with high surface area and average diameters of 140.8 nm (RHNPs) and 78.29 nm (BPBC). Kinetic studies demonstrated that adsorption followed pseudo-second-order kinetics (R2 > 0.98), with intraparticle diffusion modeling indicating multi-stage adsorption process. Remarkably, RHNPs and BPBC exhibited maximum adsorption capacities (Qmax of 94 mg/g and 93 mg/g for CV, and 75.4 and 94.95 mg/g for MB, respectively, at neutral pH (7.0) with a 0.1 g adsorbent dose. Rapid sequestration of 97% (RHNPs) and 95% (BPBC) for CV were maintained within 30 min, while MB removal reached 92% (RHNPs) and 98% (BPBC) after 120 min. The Freundlich isotherm provided strong correlations for

both RHNPs (R2 = 0.9971) and BPBC (R2 = 0.9321). The thermodynamic calculations confirm that MB adsorption is spontaneous and exothermic, whereas CV adsorption is spontaneous and endothermic. These findings underscore the potential of RHNPs and BPBC as cost-effective, high-performance alternatives for industrial wastewater remediation, aligning with circular economy and green chemistry principles by valorizing agricultural waste. Keywords Agrowaste valorization · Banana peel biochar · Dye adsorption · Freundlich isotherm · Rice husk nanoparticles · Sustainable wastewater treatmen