Removal of Methylene Blue Dye from Aqueous Solutions Using Magnetic Bleached Teawaste Adsorbent Particles: Response Surface Methodology Approach

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Abstract

The discharge of dye-containing effluents from textile and allied industries poses serious environmental challenges due to their toxicity, persistence, and adverse effects on aquatic ecosystems. In this study, magnetic bleached tea waste (MBTW) adsorbent particles were developed from waste tea biomass through bleaching, iron chloride impregnation, and thermal activation. Response Surface Methodology (RSM) was employed to evaluate the effects of activation temperature, activation time, and $FeCl_3$ dosage on the adsorption performance of MBTW for methylene blue (MB) removal. Seventeen adsorbent formulations were synthesized and screened. The optimum adsorbent was prepared at 200°C for 2 h with an $FeCl_3$ dosage of 1 g g^{-1} and exhibited an adsorption capacity of 27.87 mg g^{-1} during screening tests. Characterization by FTIR, CHNS elemental analysis, and BET surface area measurements revealed the importance of surface functional groups and magnetic activation in enhancing adsorption performance. Equilibrium data were analysed using Langmuir, Freundlich, and Sips isotherms. The Sips model provided the best fit ($R^2 = 0.966$) with a maximum adsorption capacity of 53.55 mg g^{-1}. Kinetic studies showed that adsorption followed pseudo-second-order behaviour, indicating the significance of chemisorption mechanisms. Thermodynamic analysis revealed that adsorption was spontaneous and endothermic. Regeneration studies demonstrated stable adsorption performance over five adsorption–desorption cycles. The results indicate that MBTW is a low-cost, sustainable, and efficient adsorbent for dye-contaminated wastewater treatment.

Index Terms

Adsorption, Circular Economy, Magnetic Bleached Teawaste, Waste Biomass, Wastewater Treatment