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Original Article

Porosity refinement and intensification of triarylmethane dyes adsorption on bauxite residue *via* chemical activation: parametric optimization and theoretical insights

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ABSTRACT

The widespread commercial application and low-cost synthesis of triarylmethane dyes, particularly in aquaculture as fungicides, have led to their excessive release into aquatic environments, raising serious environmental concerns. This study presents an effective strategy for removing triarylmethane dyes using chemically activated bauxite residue (BR), a waste product of the alumina industry. Chemical activation with $ZnCl_2$ significantly enhanced the surface area and porosity of BR, as confirmed by Brunauer-Emmett-Teller (BET) analysis and electron microscopy, leading to improved dye adsorption capacity. Response surface methodology (RSM) was employed for process optimization, achieving a removal efficiency of over 96% under optimal conditions: adsorbent dose of 40 g/L, dye concentration of 40 mg/L, pH 7, temperature 30°C, and stirring speed 150 rpm. The adsorption capacity at equilibrium (q_m) reached 64.93 mg/g and 41.84 mg/g for malachite green (MG) and brilliant green (BG), respectively. Model validation revealed high reliability, with correlation coefficients (R^2) of 0.989 (MG) and 0.977 (BG), and adjusted/predicted R^2 values of 0.955/0.906 (MG) and 0.962/0.916 (BG), respectively. Among the kinetic models tested, the Eovich model provided the best fit ($R^2 \approx$ 0.99) for MG, suggesting a chemisorption-dominated mechanism. Additionally, the treated effluent exhibited no antibacterial effect against *Escherichia coli*, indicating its suitability for reuse. These findings highlight the potential of $ZnCl_2$-activated BR as a sustainable and efficient adsorbent for removing triarylmethane dyes, with promising prospects for further scale-up and environmental deployment.

1. Introduction

From the genesis of early civilization, water has been a critical requirement for the well-being and progress of its people [1]. The interplay among the supply of safe water, food security, and industrial growth is so intense that the concept of "sustainable society" is unthinkable in the absence of such symbiotic and cohesive adaptation, and therefore, is accentuated in the United Nations' Sustainable Development Goals (SDGs). Yet, the presently available water sources are under tremendous stress owing to over-exploitation and relentless discharge of pollutants from anthropogenic activities. Moreover, the upsurge in global population and the urge for modern commodities have propelled an expeditious increase in urbanization and industrialization, which has further worsened water scarcity and pollution alike [2-4]. Among various chemical pollutants, synthetic dyes have been studied extensively owing to their ability to contaminate the water sources even in very small concentrations by impeding the sunlight from diffusing through the water surface, troubling not only the endurance of lower biota but also the sustenance of the aquatic food chain [5,6]. Specifically, malachite green (MG) and brilliant green (BG), a class of triarylmethane dyes, have been used for a long time in a range of manufacturing industries and have also gained popularity as fungicides in aquaculture [7,8]. However, these dyes are known to be environmental persisters with egregious toxicity towards aquatic life [9]. Clinical investigations have indicated the multi-organ toxic nature of triarylmethane dyes towards mammals. According to the investigation by Desciens and colleagues, oral dosing of these compounds has resulted in a reduction in food intake, fertility, and growth kinetics, leading to damage to the liver, spleen, kidney, and heart. Additionally, these also caused rashes and inflammation in the skin, eyes, lungs, and bones [10]. Moreover, MG dyes-fed mice are found to have apoptosis in the transitional epithelium of the urinary bladder and thyroid follicles [11]. In the case of rats, long-term exposure to MG has resulted in drastic weight loss and alteration in the serum urea and aspartate aminotransferase [12]. Several studies have suggested that MG exposure may be cytotoxic to mammalian cells and may have carcinogenic effects on the liver, thyroid, and other organs of mammals [13]. These dyes [14]. Taking note of such perilous health effects and unprecedented risks to human health, multiple nations, including the European Union (EU), the USA, and Japan, have already prohibited the use of triarylmethane dyes in aquaculture [15]. Unfortunately, as a profitable industrial ingredient, these restrictions have not been sufficient to prevent the production and subsequent

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