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Adsorption of Cd2+ Using Brick-Sludge Composite: A Circular Economy Approach

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Abstract Cadmium (Cd), a highly toxic element, often contaminates drinking water through Cd^{2+} impurities in galvanized pipelines and cadmium-based solders. This study presents a sludge-brick composite for Cd^{2+} decontamination, aligning with circular economy principles. Using Response Surface Methodology (RSM), key parameters such as pH, mixing time, and sludge proportion (V/V) were optimized, with adsorption capacity (qe) as the response variable. The qe was evaluated by testing 0.1 g of the material in a 10-cc water sample at pH 7 over 1 hour. 50 g of sludge was dispersed in 250 cc of deionized water using ultrasound for 20 minutes. The prepared solution was then combined with an additional 250 cc of deionized water and stirred at 70°C for 2 hours at a speed of 300 rpm. Subsequently, sludge percentage, the solution's pH and mixing time with 1 g of brick powder were adjusted based on the RSM pattern. The results of the RSM modeling indicated that a quadratic model with an R2 value of 0.8 and a predicted R2 of 0.7 provided a reliable framework for response optimization. ANOVA analysis revealed that sludge percentage had the greatest impact on adsorption efficiency, with an F-value of 5.17. pH was identified as the second most influential factor, followed by the mixing time of sludge and brick powder. The optimization analysis, achieving a desirability of 1, revealed that the highest Cd^{2+} adsorption performance onto the composite occurs under the following conditions: pH 7, a sludge-brick mixing time of 10 hours, and a sludge proportion of 48% during adsorbent synthesis.

Keywords: Design of Experiments; Heavy Metal Ions; Construction and Demolition Waste; Characterization; Synthesis; Mathematical Modeling

1. Introduction

Industrialization is rapidly expanding to meet demand, yet it generates significant water contamination from hazardous heavy metals like cadmium, lead, and mercury, exceeding safe levels set by WHO and the EU Water Framework Directive (2000/60/EC) [1]. These non-biodegradable pollutants from industries such as mining and electroplating pose severe health and ecological risks [2]. Adsorption stands out as a cost-effective and eco-friendly solution, utilizing materials like activated carbon and waste-derived adsorbents. This study focuses on employing brick-sludge composites (BSC) to remove heavy metals from water, aiming to optimize the sludge-to-brick ratio to enhance adsorption while minimizing secondary contamination. The approach aligns with EU Circular Economy policies and promotes sustainable remediation by repurposing waste materials, thereby reducing costs and environmental impact.

2. Materials and Methods

To optimize the synthesis of a sludge-brick composite, the study utilized Design of Experiments with Design Expert 7.0.0, Response Surface Methodology (RSM), and Central Composite Design (CCD). Key parameters—pH, mixing time, and sludge-to-brick ratio—were optimized, with adsorption capacity (qe) as the main response. Tests involved exposing 0.1 g of the composite to 10 cc water samples at pH 7 for 1 hour. Preparation included dispersing 50 g of sludge in 250 cc of deionized water via ultrasonication for 20 minutes, followed by mixing with an equal volume of deionized water at 70°C for 2 hours at 300 rpm. RSM guided adjustments in sludge proportion, pH, and mixing time with 1 g of brick powder. Inductively Coupled Plasma Mass Spectrometry (ICP-MS) quantified cadmium removal (Elan 6000, PerkinElmer, USA).

3. Results and discussions

Among the synthesis factors, sludge proportion (C) emerged as the most impactful for Cd^{2+} adsorption capacity (qe), with a P-value of 0.0720 from RSM analysis. Though not below the 0.05 threshold, it had the strongest effect. The interaction between temperature and sludge proportion (A×C) was also influential, with a P-value of 0.0719. Mixing time (A) showed moderate impact ($P = 0.2089$), while pH (B) was less significant ($P = 0.5918$). Other interactions and quadratic terms were not significant. Overall, sludge proportion most effectively enhanced Cd^{2+} adsorption capacity, while pH had minimal effect. Fig. 1(a) illustrates changes and fluctuations in Cd^{2+} adsorption capacity (qe) with varying pH and mixing time, showing an optimal combination for maximum qe. Fig. 1(b) highlights the impact of sludge proportion and mixing time, where increased sludge content leads to significant qe changes and fluctuations. Fig. 1(c) depicts how sludge proportion and pH jointly influence qe, with observable fluctuations indicating complex interactions. Fig. 1(d) confirms the model's predictive accuracy by aligning predicted and actual qe values.

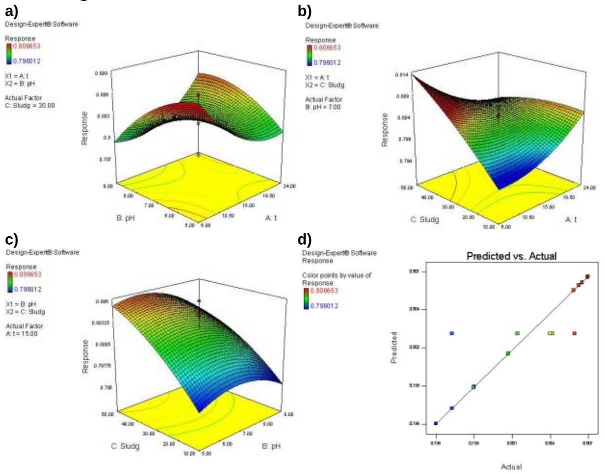

Fig. 1. The outcomes of sensitive analysis through RSM model based on: (a) pH-time vs q_e, (b) Sludge (%)-time vs q_e, (c) pH- Sludge (%) vs q_e, and (d) actual and predicted q_e.

Conclusions

This study confirms the efficiency of BSC for Cd^{2+} removal, with optimized conditions achieving high adsorption capacity. Sludge proportion was the dominant factor, followed by pH and mixing time. The approach aligns with circular economy principles and supports sustainability.

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