

Integrated adsorption and electrocoagulation for sustainable batik wastewater treatment: Synergistic optimization of pollutant removal

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ABSTRACT

The batik industry is an essential cultural and economic activity, yet it generates significant environmental challenges due to untreated wastewater containing synthetic dyes, heavy metals, and organic pollutants. These pollutants, resistant to conventional degradation methods, necessitate advanced and integrated treatment solutions. This study evaluates the combined application of adsorption and electrocoagulation for treating batik wastewater. Adsorption doses (10 g/L, 20 g/L, 30 g/L) using activated carbon and electrocoagulation at varying current densities (10 mA/cm², 20 mA/cm², 30 mA/cm²) were systematically analyzed for their effectiveness in removing chemical oxygen demand (COD), biological oxygen demand (BOD), and turbidity. Results revealed that higher adsorption doses and current densities improved removal efficiencies synergistically. Maximum removal efficiencies of 57% for COD, 46% for BOD, and 68% for turbidity were achieved under optimal conditions (30 g/L adsorption dose and 30 mA/cm² current density). These findings demonstrate the feasibility of an integrated adsorption-electrocoagulation approach as a scalable and sustainable solution for treating complex wastewater streams in the batik industry.

1. INTRODUCTION

The batik industry is a cornerstone of cultural heritage and a critical economic driver in many regions, particularly in Indonesia. However, the environmental implications of its production process are significant, primarily due to the discharge of untreated or inadequately treated wastewater. Batik wastewater is a complex mixture containing synthetic dyes, heavy metals, suspended solids, and organic pollutants, all of which pose severe threats to aquatic ecosystems and human health. These pollutants are often resistant to degradation, complicating conventional treatment methods [1]. As environmental regulations become stricter,

there is an urgent need to develop effective, sustainable, and scalable treatment methods to address the challenges posed by batik wastewater.

Among the various treatment technologies available [2]–[13], adsorption and electrocoagulation have gained significant attention for their efficacy and feasibility. Adsorption, as a pretreatment step, has been widely used to remove dyes and organic pollutants from wastewater. Adsorbents such as activated carbon, agricultural by-products, and other natural materials offer cost-effective solutions for pollutant removal due to their high surface area and affinity for various contaminants [14]. However, adsorption alone

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often falls short in treating the wide spectrum of pollutants present in batik wastewater, necessitating a complementary treatment method.

Electrocoagulation (EC) is an advanced electrochemical technology that has proven effective in removing a broad range of contaminants, including suspended solids, heavy metals, and organic pollutants. The EC process involves the in-situ generation of coagulants through the electrolytic dissolution of metal electrodes, which destabilizes and aggregates pollutants for easier removal [15]. It is considered a sustainable option due to its minimal chemical requirements and potential for sludge reduction. However, the effectiveness of EC can be influenced by wastewater characteristics such as pollutant concentration, pH, and conductivity, making it an ideal candidate for integration with pretreatment methods like adsorption.

This study focuses on the combined application of adsorption as a pretreatment step followed by electrocoagulation for batik wastewater treatment. The hybrid approach leverages the strengths of both methods: adsorption efficiently reduces the initial pollutant load, making the subsequent EC process more effective, while EC addresses pollutants that adsorption cannot adequately remove. Combining these methods is expected to provide a synergistic effect, enhancing the overall treatment efficiency and reducing operational costs [16].

The objective of this research is to evaluate the performance of this integrated treatment system in reducing key pollutants in batik wastewater, such as chemical oxygen demand (COD), color, and heavy metal concentrations. The results will provide critical insights into the feasibility and scalability of this hybrid approach for real-world applications.

2. MATERIALS AND METHOD

2. 1. Materials

2.1.1. Batik Wastewater Samples

Samples of batik wastewater were collected from a local batik production facility. The wastewater was characterized for initial

concentrations of chemical oxygen demand (COD), biological oxygen demand (BOD), and turbidity to establish baseline conditions.

2.1.2. Adsorbent

Activated carbon was selected as the adsorbent due to its high adsorption capacity and chemical stability. Adsorption doses of 10 g/L, 20 g/L, and 30 g/L were prepared by weighing the required amount of activated carbon and dispersing it into 500 mL of wastewater in separate experiments.

2.1.3. Electrocoagulation Setup

The electrocoagulation system consisted of a batch reactor equipped with aluminum electrodes (10 cm × 5 cm × 0.2 cm). The electrodes were cleaned with sandpaper and rinsed with distilled water before each run. A DC power supply was used to apply current densities of 10 mA/cm², 20 mA/cm², and 30 mA/cm². The electrode spacing was maintained at 1.5 cm throughout the experiments.

2.1.4. Chemicals

Analytical-grade sodium hydroxide (NaOH) and sulfuric acid (H₂SO₄) were used to adjust the pH of the wastewater to the desired range of 6.5–7.5 before treatment.

2.2. Methods

2.2.1. Experimental Design

The experiments were conducted to evaluate the effects of adsorption dose and current density on the removal of COD, BOD, and turbidity. A total of nine combinations of adsorption doses (10 g/L, 20 g/L, 30 g/L) and current densities (10 mA/cm², 20 mA/cm², 30 mA/cm²) were tested in a systematic manner.

2.2.2. Adsorption Process

The adsorption experiments were conducted as a pretreatment step. Activated carbon was added to 500 mL of batik wastewater at the specified doses (10 g/L, 20 g/L, 30 g/L). The mixture was stirred at 150 rpm using a magnetic stirrer for 60 minutes at room temperature to achieve equilibrium. After

treatment, the wastewater was filtered to separate the activated carbon, and the treated water was retained for the electrocoagulation process.

2.2.3. Electrocoagulation Process

The filtered wastewater from the adsorption step was subjected to the electrocoagulation process. The batch reactor was filled with 500 mL of pretreated wastewater. Current densities of 10 mA/cm², 20 mA/cm², and 30 mA/cm² were applied for 30 minutes using a DC power supply. The process was monitored to maintain a constant pH within the range of 6.5–7.5 by adding NaOH or H₂SO₄ as needed. At the end of the treatment, the wastewater was allowed to settle for 15 minutes, and samples were collected for analysis.

2.2.4. Analytical Measurements

The treated wastewater was analyzed for COD, BOD, and turbidity. Removal efficiencies for COD, BOD, and turbidity were calculated using the following formula (**equation 1**):

$$\text{Removal (\%)} = \frac{\text{Initial concentration} - \text{Final Concentration}}{\text{Initial concentration}} \times 100 \quad (1)$$

The effects of adsorption dose and current density on removal efficiencies were analyzed to determine significant interactions and optimize operational parameters.

3. RESULT AND DISCUSSION

3.1. Effect of Adsorption Dose

The adsorption dose significantly influenced the removal efficiencies of COD, BOD, and turbidity. As the adsorption dose increased from 10 g/L to 30 g/L, a noticeable improvement was observed across all parameters (**Fig 1**). This trend highlights the importance of sufficient adsorbent availability in reducing pollutant concentrations.

For COD removal, the efficiency improved from 39% at 10 g/L to 57% at 30 g/L when paired with a current density of 10 mA/cm². A similar pattern was observed across other current densities, indicating that higher adsorbent doses provide a larger surface area and more binding sites for organic pollutants, thus facilitating better adsorption. These

findings are consistent with earlier studies, including Li et al. (2025) and Tang (2024), which underscore the role of enhanced adsorption capacity in pollutant removal [17], [18].

BOD removal also increased significantly, from 32% at 10 g/L to 46% at 30 g/L. This reflects the ability of the adsorbent to capture biodegradable organic matter, thereby reducing its availability for microbial degradation during the electrocoagulation process. The results align with the studies of Japri et al. (2024) and Pamidimukkala et al. (2018), which demonstrate the efficacy of activated carbon in capturing organic pollutants [19], [20].

For turbidity removal, the efficiency rose from 46% to 68% as the adsorption dose increased from 10 g/L to 30 g/L. This improvement demonstrates that higher doses of activated carbon are more effective in trapping colloidal particles, leading to clearer treated water. Similar trends were reported by Siong et al. (2013) and Akhtar et al. (2024), emphasizing the role of adsorption in reducing suspended solids [21], [22].

Overall, these findings confirm that higher adsorbent doses enhance the removal of pollutants, primarily due to the increased adsorption capacity. However, beyond a certain threshold, the improvement may plateau, likely due to saturation of the adsorption sites. This suggests that optimizing the adsorption dose is essential for achieving cost-effective treatment without unnecessary resource expenditure.

3.2. Effect of Current Density

Current density was another critical factor influencing the performance of electrocoagulation. Higher current densities consistently resulted in better removal efficiencies across all parameters. This improvement can be attributed to the increased generation of coagulants and hydrogen bubbles, which enhance the destabilization and removal of pollutants.

For COD removal, the efficiency increased from 39% at 10 mA/cm² to 57% at 30 mA/cm²,

with a 10 g/L adsorption dose. This pattern was consistent across all adsorption doses, with maximum removal observed at the highest current density. The enhanced performance can be attributed to the increased production of metal hydroxide flocs, which effectively capture dissolved and colloidal organic matter. These observations align with the findings of Agarwal et al. (2024) and Moreno-Casillas (2007), who emphasized the role of floc formation in improving COD removal [23], [24].

BOD removal showed a similar trend, increasing from 32% to 46% with rising current density. This improvement highlights the combined effects of adsorption and electrochemical oxidation, which help break down and aggregate biodegradable organics. Similar results were reported by Reátegui-Romero et al. (2020) and Alkurdi and Abbar (2020), demonstrating the impact of current density on electrocoagulation efficiency [25], [26].

Turbidity removal efficiency also increased, from 46% at 10 mA/cm² to 68% at 30 mA/cm². This underscores the role of current density in generating sufficient flocs to capture suspended and colloidal particles. These results are consistent with findings from Sadeddin et al. (2011) and Behera (2025), who observed significant reductions in turbidity in industrial wastewater treated via electrocoagulation [27], [28].

While higher current densities improve removal efficiencies, they also increase energy consumption and the potential for electrode degradation. Therefore, it is critical to optimize the current density to balance efficiency and cost.

3.3. Combined Effects of Adsorption Dose and Current Density

The combined effects of adsorption dose and current density were synergistic, with the highest removal efficiencies observed at the maximum levels of both parameters, specifically 30 g/L and 30 mA/cm². The results confirm that combining adsorption and electrocoagulation effectively leverages the strengths of both methods.

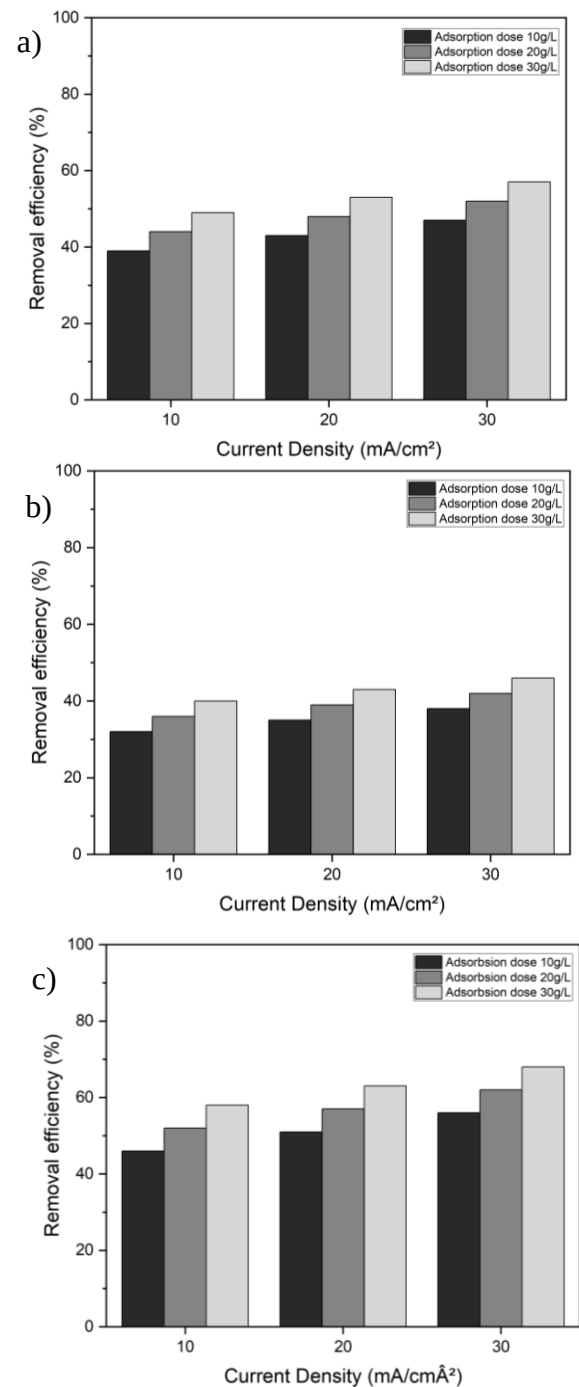


Figure 1. Combined Effects of Adsorption Dose and Current Density on removal of : a. COD; b. BOD; and c. Turbidity

Adsorption serves as a preparatory step by reducing the initial pollutant load, thereby improving the efficiency of the electrocoagulation process. On the other hand, electrocoagulation complements adsorption by addressing residual pollutants and enhancing the removal of turbidity and suspended solids. This synergy is evident in the maximum removal efficiencies achieved under

optimal conditions: 57% for COD, 46% for BOD, and 68% for turbidity. These values significantly surpass those achievable by either method alone, highlighting the value of an integrated approach. Similar findings have been reported by Graca et al. (2022) and Linares-Hernández et al. (2007), who demonstrated the advantages of combining adsorption and electrocoagulation for wastewater treatment [29], [30].

The results emphasize the potential of a hybrid adsorption-electrocoagulation system as a robust and scalable solution for treating batik wastewater. By leveraging the complementary strengths of both methods, this integrated approach offers a practical and efficient means of reducing complex pollutant loads, aligning with recent advancements in water treatment technologies.

4. CONCLUSION

This study demonstrates the effectiveness of a hybrid adsorption-electrocoagulation system for treating batik wastewater. The results indicate that both adsorption dose and current density significantly influence pollutant removal efficiencies. Higher adsorption doses (up to 30 g/L) enhance the system's ability to reduce COD, BOD, and turbidity by providing increased surface area and binding sites for pollutants. Similarly, higher current densities (up to 30 mA/cm²) improve the generation of coagulants and hydrogen bubbles, leading to enhanced aggregation and removal of residual pollutants.

The combination of adsorption and electrocoagulation proved synergistic, achieving maximum removal efficiencies of 57% for COD, 46% for BOD, and 68% for turbidity under optimal conditions. This integrated approach addresses the limitations of individual methods and highlights its potential as a robust, scalable, and sustainable treatment solution for batik wastewater. The findings align with recent advancements in water treatment technologies and provide a pathway for industrial-scale application,

particularly for small and medium-sized enterprises in the batik sector.

Future research should focus on optimizing operational parameters, such as pH and reaction time, and exploring cost-effective alternatives to activated carbon. Economic feasibility studies and long-term assessments of electrode durability are also recommended to ensure the practicality and sustainability of this hybrid system.

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