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Combined Zeolite Pre-Treatment and Electrocoagulation for Effective Heavy Metal and Turbidity Removal in Electroplating Effluent

Muhammad Akbar Febrianto [1,*], Casabella Aguilera [2]

[1]*Department of Environmental Engineering, Universitas PGRI Adi Buana, Surabaya, Indonesia*

[2]*Centro de Estudios y Servicios Ambientales de Villa Clara (CESAMVC), Cuba*

**Corresponding Author: E-mail:* makbarfeb9@gmail.com

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Abstract

Electroplating industries produce wastewater containing high levels of heavy metals and other pollutants, posing serious environmental and health risks. This study examines a two-stage treatment approach that combines zeolite adsorption as a pre-treatment and electrocoagulation as the primary treatment. Zeolite adsorption effectively reduced chromium (Cr) and turbidity by 49.12% and 40%, respectively, at an optimal dosage of 15 g/L, significantly lowering the pollutant load for subsequent treatment. The electrocoagulation process further enhanced removal, achieving maximum reductions in Cr (82.76%) and turbidity (80.95%) at 30 V and 90 minutes of treatment. This integrated system demonstrated a synergistic effect, addressing the limitations of standalone technologies by combining the high adsorption capacity of zeolite with the coagulant generation efficiency of electrocoagulation. Additionally, the method minimized sludge generation and reduced operational costs, offering a sustainable and effective solution for electroplating wastewater treatment. The study provides valuable insights for optimizing industrial wastewater management to meet stringent environmental standards.

1. Introduction

Electroplating industries play a significant role in driving global economic growth by contributing to sectors such as automotive, electronics, and manufacturing. These industries, however, are a substantial source of environmental challenges due to the generation of wastewater rich in heavy metals and other hazardous substances. Electroplating wastewater typically contains pollutants like chromium (Cr), nickel (Ni), zinc (Zn), and other toxic metals that, if not adequately treated, pose significant risks to aquatic ecosystems, soil quality, and human health [1]. Addressing this issue is essential not only for environmental sustainability but also to meet increasingly stringent regulatory standards.

Heavy metals in electroplating wastewater are non-biodegradable and can accumulate in living organisms, causing severe health impacts, including carcinogenic effects, organ damage, and developmental disorders. The release of untreated wastewater into natural water bodies disrupts aquatic ecosystems by contaminating the food chain and degrading water quality [2]. These pressing concerns highlight the urgent need for effective and efficient treatment methods to mitigate the environmental footprint of electroplating industries.

Conventional wastewater treatment methods, such as chemical precipitation, ion exchange, and membrane filtration, have been widely utilized to address heavy metal contamination [3]–[15]. Chemical precipitation involves adding chemicals to form insoluble metal hydroxides, which can be removed by sedimentation. Ion exchange techniques use resins to selectively remove heavy metals, while membrane filtration employs physical barriers to separate contaminants. Despite their effectiveness in specific scenarios, these methods often face significant challenges, including high operational costs, the generation of secondary waste (e.g., chemical sludge), and reduced performance when dealing with fluctuating wastewater compositions [16]. These limitations necessitate exploring alternative or hybrid technologies that are both cost-effective and environmentally friendly.

Electrocoagulation (EC) has emerged as a promising electrochemical treatment technology for removing heavy metals, organic matter, and suspended solids. This method uses an electrical current to generate coagulants in situ, destabilizing and aggregating pollutants, facilitating their removal. The advantages of EC include its simplicity, low chemical usage, and minimal sludge production compared to traditional methods [17]. However, while EC is highly effective for initial contaminant removal, some pollutants may persist in the treated effluent, necessitating further treatment to meet discharge standards.

Zeolite, a natural or synthetic microporous material, is well-regarded for its high adsorption capacity and selectivity for heavy metals. The use of zeolite in wastewater treatment relies on mechanisms such as ion exchange and surface adsorption, which are particularly effective in capturing dissolved metals like Cr, Ni, and Zn [18], [19]. Furthermore, zeolite is abundant, cost-effective, and reusable after regeneration, making it an attractive option for wastewater polishing applications.

By combining the strengths of both technologies, zeolite adsorption is utilized as an initial treatment to reduce dissolved heavy metals and other contaminants, thereby effectively lowering the pollutant load for subsequent electrocoagulation. Electrocoagulation, in turn, removes suspended solids and remaining pollutants, addressing the limitations of standalone systems such as the restricted adsorption capacity of zeolite or the high chemical demand of electrocoagulation when used independently. This integrated approach enhances the overall removal efficiency of key pollutants, including heavy metals and turbidity, while minimizing sludge generation and operational costs.

This study aims to evaluate the effectiveness of integrating electrocoagulation and zeolite adsorption as a combined treatment method for electroplating wastewater. By addressing these goals, the study aims to develop innovative, cost-effective, and sustainable solutions for managing electroplating wastewater.

2. Materials and Methods

2.1. Materials

2.1.1. Electroplating Wastewater

The electroplating wastewater used in this study was collected from a local electroplating facility. The wastewater was analyzed to determine its initial characteristics, including a chromium (Cr) concentration of 57 mg/L and a turbidity of 35 NTU. These values indicate significant pollution levels, necessitating effective treatment to meet environmental discharge standards.

2.1.2. Electrocoagulation Setup

An iron (Fe) electrode was used as both a sacrificial anode and a cathode. The electrodes were cut into plates (dimensions: 10 cm × 5 cm × 0.2 cm) and cleaned with sandpaper and distilled water before use. A DC power supply unit with adjustable voltage and current was used to apply electrical currents. A 1.5 L acrylic reactor equipped with an agitator was used to hold the wastewater during treatment.

2.1.3. Zeolite Adsorption Materials

Natural zeolite was obtained from a local supplier. The zeolite was crushed and sieved to a particle size of 1–2 mm, then activated with 0.1 M HCl to enhance its adsorption capacity. The zeolite was then washed with distilled water and dried at 105°C for 24 hours.

2.2. Methods

2.2.1. Experimental Design

The study was conducted in two stages: Zeolite Adsorption. This pre-treatment stage focused on polishing the effluent by removing residual heavy metals. Electrocoagulation Treatment. This primary treatment stage aimed to remove suspended solids and significantly reduce heavy metal concentrations.

2.2.2. Zeolite Adsorption Process

In the pre-treatment stage, raw electroplating wastewater was passed through a column packed with activated zeolite. The zeolite was prepared by activation with 0.1 M HCl, followed by rinsing with distilled water and drying. The process parameters were varied, including zeolite dosages (5, 10, and 15 g/L), to optimize the removal of heavy metals. The treated effluent from this stage was collected and analyzed to determine the concentration of key pollutant chromium (Cr) before proceeding to the electrocoagulation stage.

2.2.3. Electrocoagulation Process

In the primary treatment stage, the effluent from the zeolite adsorption process was treated in an electrocoagulation reactor equipped with aluminum and iron electrodes spaced 5 cm apart. The reactor was connected to a DC power supply, and the treatment was performed at varying voltage levels (10 V, 20 V, and 30 V) and durations (20 minutes, 60 minutes, and 90 minutes). The wastewater pH was adjusted to 7.0 before initiating the process. The final treated effluent was analyzed to evaluate the overall performance of the integrated system.

2.2.4. Analysis of Parameters

Atomic Absorption Spectroscopy (AAS) was used to measure Cr concentrations. A turbidity meter was used to evaluate the removal efficiency of suspended solids.

3. Results and Discussions

3.1. Zeolite Adsorption

3.1.1. Effect of Zeolite Dosage on Chromium Removal

The initial chromium concentration in the electroplating wastewater was 57 mg/L. With increasing zeolite dosage from 5 g/L to 15 g/L, the reduction in chromium concentration improved significantly. At a dosage of 5 g/L, the final chromium concentration decreased to 48 mg/L, achieving a reduction efficiency of 15.79%. When the dosage was increased to 10 g/L, the final chromium concentration was further reduced to 37 mg/L, corresponding to a reduction efficiency of 35.09%. At the highest dosage of 15 g/L, the chromium concentration was reduced to 29 mg/L, achieving a maximum reduction efficiency of 49.12% (**Fig 1**). These results are consistent with previous studies, which highlight the high selectivity and adsorption capacity of zeolite for heavy metals, such as chromium, due to its microporous structure and ion-exchange properties [20].

This trend suggests that higher zeolite dosages increase the availability of adsorption sites, enabling more effective binding of chromium ions. The enhanced performance at higher dosages can also be attributed to improved contact between the zeolite particles and chromium ions in the wastewater. However, the diminishing returns observed between 10 g/L and 15 g/L suggest that beyond a certain point, the adsorption capacity may approach saturation [21].

3.1.2. Effect of Zeolite Dosage on Turbidity Reduction

Similarly, turbidity reduction improved with increasing zeolite dosage. The initial turbidity of the wastewater was 35 NTU. At a zeolite dosage of 5 g/L, the final turbidity decreased to 32 NTU, resulting in an 8.57% reduction efficiency. When the dosage was increased to 10 g/L, the final turbidity was further reduced to 26 NTU, corresponding to a reduction efficiency of 25.71%. At the highest dosage of 15 g/L, turbidity decreased to 21 NTU, achieving a maximum reduction of 40% (**Figure 1**). Similar findings have been reported, where zeolite effectively removed suspended solids and colloidal particles, attributed to its high surface area and adsorption properties [22], [23].

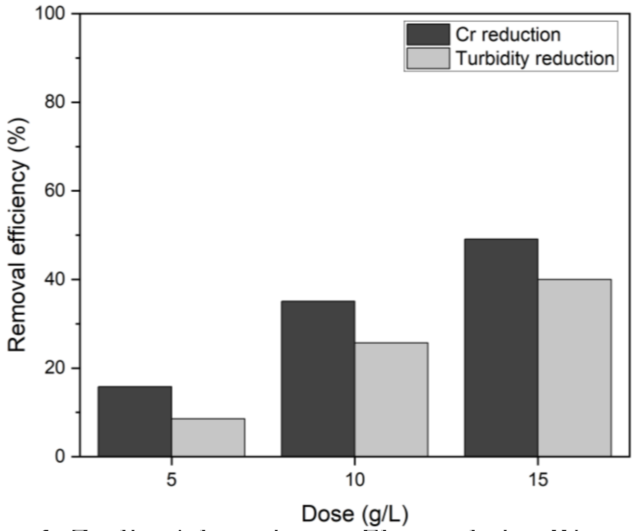

Figure 1. Zeolite Adsorption on Electroplating Wastewater

The reduction in turbidity reflects the zeolite's ability to adsorb suspended solids and colloidal particles present in the wastewater. Similar to chromium removal, the improved turbidity reduction at higher dosages can be linked to the increased surface area and adsorption capacity of the zeolite. However, as with chromium, a point of diminishing returns is observed, indicating that further dosage increases may not yield proportional improvements [24].

3.1.3. Optimal Zeolite Dosage

Based on the results, a dosage of 15 g/L was identified as the optimal condition for both chromium and turbidity reduction. At this dosage, the final concentrations of chromium (29 mg/L) and turbidity (21 NTU) were lowest, with reduction efficiencies of 49.12% and 40%, respectively. These results demonstrate the potential of zeolite adsorption to significantly reduce pollutant loads in electroplating wastewater, making it a suitable pre-treatment method for subsequent treatment stages such as electrocoagulation [25], [26].

3.2. Electrocoagulation

3.2.1. Effect of Voltage and Duration on Chromium Removal

The initial chromium concentration from the pre-treatment stage was 29 mg/L. The results showed that both voltage and duration had a direct impact on chromium removal efficiency. At 10 V, chromium reduction increased progressively with treatment duration, reaching a maximum efficiency of 65.52% at 90 minutes. When the voltage was increased to 20 V, the efficiency further improved, reaching 72.41% at 90 minutes. At 30 V, the system achieved its best performance, with a maximum chromium reduction efficiency of 82.76% at 90 minutes (**Figure 2**). These findings are consistent with previous studies that emphasize the role of voltage in enhancing the generation of coagulants and improving heavy metal removal efficiency [27], [28].

This trend underscores the crucial role of voltage in generating coagulants through electrode dissolution, thereby facilitating the aggregation and removal of chromium ions. Higher voltages increase the production of coagulants and enhance electrochemical reactions, thereby improving removal efficiency. However, the results also indicate that prolonged treatment durations allow for more complete removal, as the interaction between chromium ions and coagulants becomes more effective over time [29].

3.2.2. Effect of Voltage and Duration on Turbidity Reduction

The initial turbidity of 21 NTU from the pre-treatment stage was also significantly reduced during the electrocoagulation process. At 10 V, turbidity reduction efficiencies ranged from 23.81% at 30 minutes to 61.90% at 90 minutes. Increasing the voltage to 20 V further enhanced the reduction, with efficiencies reaching 71.43% at 90 minutes. The best performance was observed at 30 V, where turbidity was reduced by 80.95% at 90 minutes. Similar studies have reported that higher voltages and longer durations increase the destabilization and aggregation of colloidal particles, which facilitates their removal through sedimentation [30].

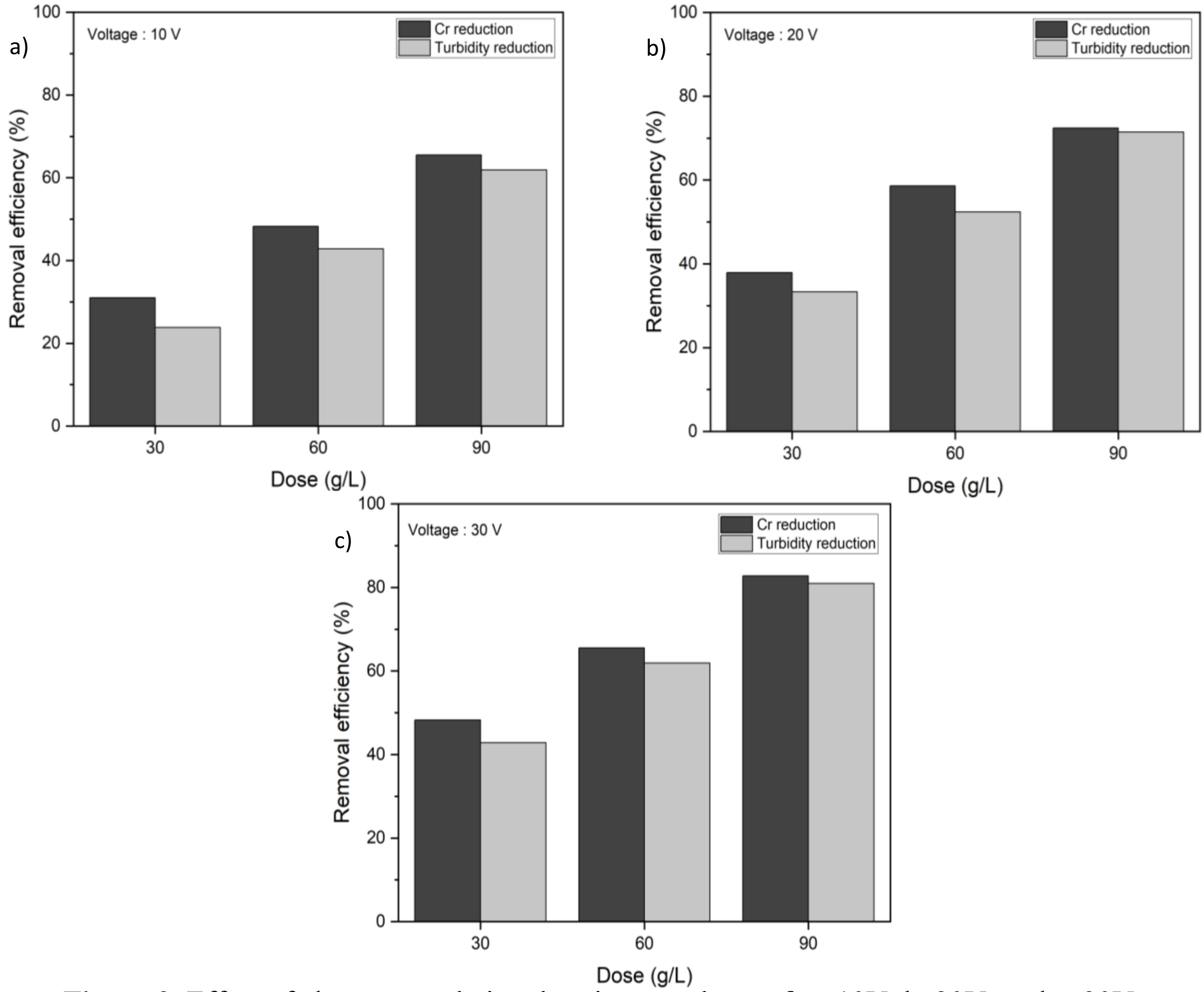

Figure 2. Effect of electrocoagulation duration at voltage of: a. 10V; b. 20V; and c. 30V

The reduction in turbidity can be attributed to the effective removal of suspended solids and colloidal particles during the electrocoagulation process. Higher voltages accelerate the destabilization and aggregation of these particles, allowing them to settle more effectively. Longer durations also provide more time for particle aggregation and sedimentation, contributing to improved turbidity reduction [31], [32].

3.2.3. Optimal Operating Conditions

The greatest reductions in chromium and turbidity were achieved at 30 V and 90 minutes of treatment. Under these conditions, chromium concentration was reduced to 5 mg/L (82.76% reduction), and turbidity was decreased to 4 NTU (80.95% reduction). These results align with prior research that highlights the effectiveness of electrocoagulation at higher voltages and extended treatment times for achieving high pollutant removal efficiencies [33].

However, the trade-offs between efficiency and energy consumption must be considered for practical applications. Higher voltages and longer durations may lead to increased operational costs and higher energy consumption. Therefore, for industrial-scale applications, a balance must be struck between achieving adequate removal efficiencies and minimizing energy consumption.

The integration of zeolite adsorption as a pre-treatment step significantly enhanced the overall performance of the electrocoagulation process. By reducing the initial chromium concentration from 57 mg/L to 29 mg/L and turbidity from 35 NTU to 21 NTU, the pre-treatment effectively reduced the pollutant load, enabling the electrocoagulation process to operate more efficiently. This two-stage approach demonstrates the synergistic potential of combining adsorption and electrocoagulation for treating complex industrial wastewater.

4. Conclusions

The study successfully demonstrated the effectiveness of integrating zeolite adsorption and electrocoagulation for treating electroplating wastewater. Zeolite adsorption, employed as a pre-treatment step, significantly reduced the initial pollutant load, lowering chromium concentrations and turbidity by 49.12% and 40%, respectively, at an optimal dosage of 15 g/L. Electrocoagulation further enhanced the treatment, achieving maximum reductions of 82.76% in chromium and 80.95% in turbidity at 30 V and 90 minutes. This integrated approach offers several advantages, including high removal efficiencies for heavy metals and turbidity, reduced sludge generation, and operational cost-effectiveness. The results emphasize the importance of combining complementary technologies to overcome the limitations of standalone systems.

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CRediT author statement

Casabella Aguilera : formal analysis, data curation, visualization, draw conclusion, validation, and writing original draft. **Muhammad Akbar Febrianto** : conceptualization, methodology, supervision, validation, investigation, funding acquisition, review whole manuscript, writing original draft.

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