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Full Paper

Elimination of Copper from Wastewater Arising from Metal Plating Through Electrocoagulation

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Abstract- The pollution of aquatic ecosystems by heavy metals poses a significant and immediate environmental threat worldwide. Industrial operations often result in the direct discharge of effluents into rivers, lakes, and ponds, leading to the contamination of these water bodies. Subsequently, these pollutants can percolate into groundwater systems through a range of transport mechanisms. Although certain heavy metals play essential roles in the metabolic processes of organisms, their elevated concentrations in aquatic environments present substantial risks, disrupting ecological balance and potentially affecting human health. This study examines the process of copper (Cu) removal from wastewater using electrocoagulation techniques. The research found that the effectiveness of copper extraction increased with extended electrocoagulation times, higher concentrations of sodium chloride (NaCl), and elevated applied electric currents. The most efficient removal was achieved under optimal conditions, which is defined as an average pH level of about 4 and a current of 2 A , and a duration of electrolysis set at 60 minutes.

Keywords- Wastewater; Heavy metals; Electrocoagulation; Copper; Electric currents

1. INTRODUCTION

The rapid acceleration in population growth, coupled with the processes of urbanization and industrialization, has culminated in the proliferation of diverse forms of wastewater. This multifaceted waste, encompassing domestic, industrial, and agricultural effluents, poses significant challenges for environmental management and sustainable development [1-2]. The discharge of wastewater has the potential to contaminate surface water, groundwater, and soil. This environmental degradation arises from the presence of diverse organic and inorganic contaminants, which include complex chemical structures, heavily metallic and other hazardous substances. These pollutants, can permeate ecosystems, leading to long-term detrimental effects on both environmental and public health [3-5]. Heavy metal contamination constitutes a critical global environmental issue with profound implications for ecosystems, human health, and biodiversity. The pervasive distribution of these hazardous elements across both natural and anthropogenically influenced environments underscores the pressing necessity for meticulous monitoring, the implementation of advanced remediation techniques, and the establishment of stringent regulatory frameworks. These measures are imperative to mitigate the adverse impacts of heavy metals on living organisms and to preserve ecological equilibrium [6-8].

Industrial wastewater frequently contains metal ion concentrations that exceed regulatory limits, posing significant environmental and health risks. The electroplating industry is particularly notorious for generating substantial volumes of metal-laden effluent. This wastewater typically contains a range of toxic metals, including copper (Cu), chromium (Cr), lead (Pb), mercury (Hg), nickel (Ni), cadmium (Cd), cobalt (Co) and zinc (Zn), among others. The presence of these metals in concentrations above permissible thresholds necessitates advanced treatment methods to mitigate their detrimental impact on ecosystems and human health. Heavy metals pose significant environmental hazards due to their ability to persist in ecosystems and bioaccumulate in living organisms. Even at trace concentrations, these toxic substances can lead to profound disruptions in ecological balance, contaminating water, soil, and air. The chronic exposure to such metals can trigger a wide spectrum of adverse health effects in humans, including neurotoxicity, organ damage, and increased susceptibility to various diseases. The insidious nature of heavy metal toxicity underscores the critical need for stringent monitoring and regulation to mitigate their impact on both environmental and public health [9]. These substances can infiltrate the human body through various vectors, including ingestion of contaminated food, inhalation of polluted air, and absorption of tainted water. Over time, they accumulate progressively within biological tissues, leading to bioaccumulation, a process that amplifies their concentration and potential toxicity [10]. Given the inherently low solubility of heavy metals in wastewater, these substances resist natural degradation processes. Consequently, they exhibit a pronounced tendency to persist within the aquatic environment, leading to their progressive accumulation over time. The extraction of toxic heavy metals from wastewater is regarded as one of the most critical domains in water treatment. This is due to the substantial environmental hazards posed by the significant quantities of dangerous contaminants discharged by numerous industrial activities. The persistent release of these harmful substances necessitates advanced and highly efficient remediation techniques to mitigate their detrimental impact on both ecosystems and human health [11]. Consequently, the implementation of appropriate methodologies for the remediation of wastewater contaminated with heavy metals is of paramount importance [12,13].

The use of electrocoagulation (EC) represents an innovative approach for water and wastewater treatment, integrating the benefits of coagulation, flotation, and electrochemical processes. This advanced technique harnesses the synergistic effects of these processes to enhance the removal of contaminants from aqueous systems. In EC, the application of an electric current generates coagulant species in situ, facilitating the agglomeration and subsequent removal of particulate matter and dissolved impurities through flotation mechanisms. The combination of these processes optimizes the overall efficiency and effectiveness of water purification, offering a promising alternative to conventional treatment methods. The electrochemical method in question represents a highly effective approach for the purification of diverse categories of contaminated water. This technique has garnered considerable attention recently due to its exceptional efficiency in the elimination of a broad spectrum of pollutants. This methodology has demonstrated exceptional efficacy in the remediation of both organic and inorganic pollutants. It operates with remarkable efficiency, generating minimal to negligible by-product waste. The process is characterized by its ability to effectively eliminate contaminants while maintaining a low environmental impact, thereby ensuring that secondary waste production remains minimal [14,15]. Numerous investigations have been concentrated on the application of electrocoagulation as a method for the treatment of diverse categories of wastewater. This includes the remediation of polluted groundwater as well as the treatment of effluents characterized by high levels of contamination, such as those originating from refineries [16-21]. They have undertaken a thorough investigation into the efficacy of the electrocoagulation process for the extraction of toxic metals from industrial effluents. This assessment encompassed an exhaustive analysis of the process's efficiency in the removal of contaminants, offering pivotal insights into its operational performance and prospective applications within the domain of wastewater treatment.

In the field of health, copper (Cu) represents a malleable, ductile metal with exceptional electrical and thermal conductivity. As a vital trace element, copper plays a crucial role in the metabolic processes of all living organisms. It is an integral part of the respiratory enzyme complex cytochrome c oxidase, which is essential for cellular respiration and energy production. Copper exists in two oxidation states, Cu^{+} (cuprous) and Cu^{2+} (cupric), both of which participate in various biochemical reactions and are essential for maintaining physiological homeostasis [22,23]. It plays an important role in many tissues, including liver, muscle and bone. Today, copper compounds are widely used for their bacteriostatic effects as antimicrobial agents. They are also used as fungicides and are commonly used for wood preservation due to their protective properties. Additionally, copper sulfate ($CuSO_4$) is widely used as an algicide in aquatic environments, where it helps to regulate algae growth and ensure the stability of aquatic ecosystems [24]. High concentrations of copper (Cu) found in processed drinking water have been associated with a range of adverse health effects. These include the onset of anemia, eye and skin irritation, and significant damage to vital organs such as the brain and heart. Prolonged exposure to high levels of copper can disrupt essential physiological functions, contributing to acute and chronic conditions that affect overall human health [25].

In an electrocoagulation (EC) system, a pair of electrodes is placed within the electrochemical reactor, where the anode, typically composed of iron or aluminum, serves as the sacrificial material responsible for generating the coagulant. When aluminum is utilized as the anode, aluminum ions (Al^{3+}) are released at the anode, while hydroxyl ions (OH^-) are generated at the cathode. Under alkaline conditions, the aluminum hydroxide [$Al(OH)_3$] formed via these reactions precipitates. Extensive research has previously been conducted to investigate the feasibility and efficiency of electrocoagulation for industrial wastewater treatment, particularly in removing heavy metals and other contaminants, thereby highlighting its potential as a sustainable alternative to conventional treatment methods [26-29].

Several research initiatives have been specifically directed towards the efficient removal of heavy metal ions from various environments, aiming to address their toxicological impacts and environmental persistence [30-32]. These efforts encompass a range of advanced techniques, including adsorption, precipitation, and membrane filtration, with a focus on optimizing removal efficiency, cost-effectiveness, and sustainability. Huang et al. investigated the influence of coexisting anions on the formation of aluminum coagulants, demonstrating that the presence of these anions significantly affects the removal efficiency of metal ions from aqueous solutions. Their findings indicate that the interaction between aluminum species and various anions can alter the coagulation process, thereby enhancing the overall efficacy of metal ion removal [32]. A separate investigation was carried out on behalf of the United States Air Force to assess the efficacy of electrocoagulation (EC) in the removal of heavy metals, specifically chromium, cadmium, nickel, and fluoride, from leachate produced during the processing of spent abrasive blast media. This study aimed to determine the potential of EC as a treatment method for mitigating the environmental impacts associated with the disposal of such materials [33]. In recent studies, a variety of researchers have explored the effectiveness of electrocoagulation (EC) in the removal of multiple heavy metals from different types of wastewaters. The results of these investigations underscore the promise of EC as a viable technology for addressing heavy metal pollution in wastewater treatment systems [34-38]. Electrocoagulation (EC) has demonstrated the ability to achieve effective removal of heavy metals through the manipulation of various operational parameters, with optimal conditions thoroughly documented in the literature. Nonetheless, limited research has elucidated the competitive adsorption phenomena involving coexisting heavy metal ions throughout the EC process. Heidmann and Calmano posited that the principal mechanism underlying the removal of zinc, copper, nickel, and silver ions is the formation of heavy metal hydroxides, which occurs in conjunction with coprecipitation with aluminum hydroxide [39]. Nevertheless, Adhoum et al. indicated that the optimal electrocoagulation (EC) conditions for the effective removal of heavy metals occur within a pH range of 4 to 8. This range is critical for maximizing the efficiency of the EC process, as it influences the solubility and availability of metal ions, thereby enhancing the overall removal efficacy [40].

The adsorption process represents an alternative approach that has been extensively utilized in numerous studies owing to its operational simplicity, remarkable efficiency, and cost-effectiveness for the remediation of heavy metal contaminants. This method involves the uptake of metal ions onto the surface of adsorbents, which facilitates their removal from aqueous solutions. The inherent advantages of adsorption include its straightforward implementation, high removal capacity, and economic feasibility, making it a favored technique for addressing heavy metal pollution [41,42]. Numerous varieties of adsorbent materials have been employed in the adsorption of metal ions. These adsorbents encompass a diverse range of substances, including but not limited to activated carbon, zeolites, and various types of biomaterials. The effectiveness of each adsorbent is influenced by its unique physical and chemical properties, such as surface area, pore structure, and functional group availability. Research has demonstrated that the selection of an appropriate adsorbent is crucial for optimizing the efficiency of metal ion removal processes in various environmental and industrial applications [43-45]. A comprehensive investigation was conducted to assess the efficacy of electrocoagulation in the removal of copper (Cu), chromium (Cr), and nickel (Ni) from wastewater generated by metal electroplating processes. This study employed an electrocoagulation approach utilizing iron and aluminum electrodes, which were arranged in a monopolar configuration [46].

Another effective and straightforward method for large-scale purification is chemical coagulation. This approach uses a variety of salts of hydrolyzed inorganic metals - like aluminum sulfate and iron chloride - as well as cationic, anionic and amphoteric agents as coagulants [47] and effective removal of colloidal pollutants and total organic content from high turbidity effluents can be achieved with great efficiency [48,49]. From a practical point of view, however, treatment costs remain significant, the volume of sludge generated is large, and the processes show a high dependence on pH levels [50,51]. Electrocoagulation has been proven as an advanced, highly effective and promising method for water treatment, as evidenced by controlled experiments involving different models of pollutants [52-58]. Nevertheless, this electrochemical method requires optimization for full-scale or industrial applications, especially for the treatment of artisanal wastewater contaminated by colloidal contaminants [59].

The purpose of this research aimed to examine the effectiveness of using electrocoagulation to extract trace metals from electroplating wastewater. Our results present valuable insights into the effectiveness of this technique for the removal of heavy metals from an effluent characterized by high concentrations of these pollutants. This research contributes to the understanding of electrocoagulation's potential in treating industrial wastewater characterized by elevated levels of toxic metal pollutants, offering a promising solution for environmental protection and regulatory compliance.

2. EXPERIMENTAL SECTION

Electroplating wastewater was sourced from a manufacturing facility located in Casablanca and subjected to comprehensive analysis to determine several critical parameters, including its pH, its alkalinity, its total solids, and heavy metal concentrations such as chromium, copper, as well as zinc. For the preparation of synthetic wastewater, a 1 g/L copper stock solution was used, which was prepared using electrolytic copper wires as the source material.

2.1. Theoretical Framework of Electrocoagulation

The electrocoagulation process operates on the principle of utilizing soluble anodes. This method entails the dissolution of these anodes, which promotes the removal of contaminants through electrochemical reactions, thereby enhancing the overall quality of the treated water [60]. In this process, an electric current is passed through two aluminum electrodes immersed in an electrolytic bath within a reactor.

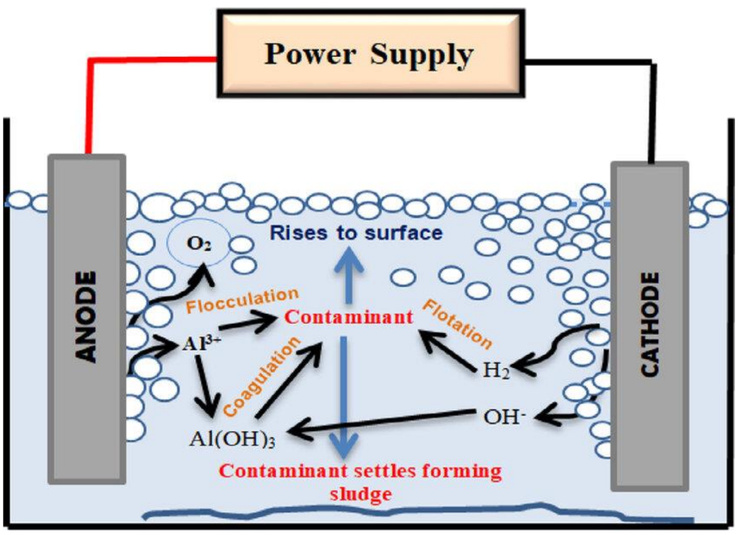

Figure 1. Electrocoagulation operating principle [62]

The current induces the formation of Al^{3+}(aq) ions, which serve as effective coagulation agents within the solution, thereby facilitating the flocculation and coagulation of targeted pollutants. Additionally, electrolysis promotes the coagulation of dissolved substances that are either oxidizable or reducible present in the effluent. The application of an electric field accelerates the migration of ions and charged particles, leading to the aggregation of suspended particles into larger flocs. These flocs can subsequently be removed through conventional physical processes, including sedimentation, flotation, or filtration [61]. The operational mechanism of the electrocoagulation process based on aluminum plates is presented in Figure 1.

2.2. Pilot device

Electrocoagulation cell is made from a durable plastic vessel designed to hold an overall volume of 2 liters of wastewater for each experimental run. Sacrificial electrodes, composed of aluminum (Al), were employed, each with dimensions of 8 cm in height, 14 cm in width, as well as 1 mm for thickness, all illustrated in Figure 2. These electrodes were arranged in a monopole configuration within the electrochemical reactor. The reactor was equipped with six aluminum plates, with a fixed inter-electrode spacing of 15 mm. The electrocoagulation process was maintained under a steady current, regulated by a direct current energy source, capable of delivering currents within the ranges of 0-5 A and voltages of 0-30 V.

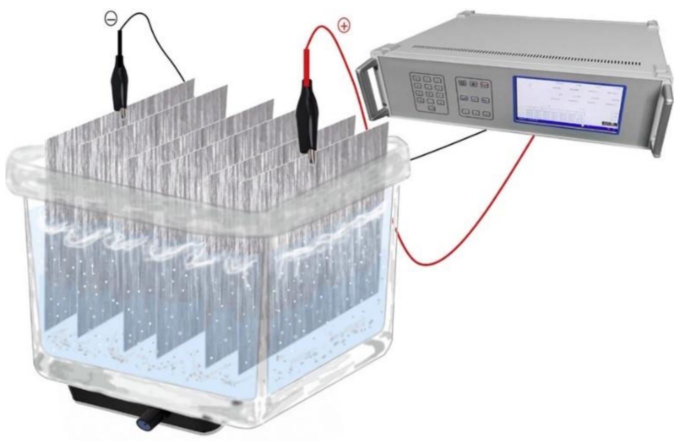

Figure 2. Experimental reactor used for electrocoagulation

2.3. Reactions of the electrodes.

In the cathodic compartment of the electrochemical (EC) system, localized generation of hydroxyl ions occurs as a result of the reduction reactions involving water and oxygen, as represented by the following equations [63]:

$$2\ H_2O_{(liq)} + 2e^- \rightarrow H_{2(g)} + 2\ OH^-_{(aq)} \qquad \textbf{Eq. 1}$$

$$2\ H_2O_{(liq)} + O_2 + 4e^- \rightarrow 4\ OH^-_{(aq)} \qquad \textbf{Eq. 2}$$

Employing an aluminum sheet as the consumable anode initiates the electrochemical oxidation of aluminum, leading to the formation of Al^{3+} ions. This process involves the transfer of electrons from the aluminum to the electrolyte, resulting in the liberation of aluminum ions into the solution and contributing to the system's electrochemical dynamics.

$$Al_{(s)} \rightarrow Al^{3+}_{(aq)} + 3e^{-} \qquad \textbf{Eq. 3}$$

Within an electrocoagulation (EC) system, aluminum hydroxide is expected to precipitate from the bulk solution, resulting in the formation of colloidal suspended particles. This process is driven by electrochemical reactions that promote the destabilization and aggregation of hydroxide ions, ultimately leading to the generation of aluminum hydroxide in a colloidal state. The properties of these suspended particles, such as their dimensions and stability, are affected by several factors, including the pH level, current density, and concentration of aluminum ions present in the solution.

$$Al^{3+}_{(aq)\,)} + 3\ OH^{-}_{(aq)} \rightarrow Al(OH)_{3(s)} \qquad \textbf{Eq. 4}$$

2.4. Experimental Studies

The investigation focused on the impact of varying pH levels (specifically 4, 6, and 8), applied current intensities (namely 1, 1.5, and 2 amperes), and contact durations (ranging from 0 to 60 minutes) on the electrocoagulation process. To control the pH and adjust the electrical conductivity of the solutions, we used a 0.1 N solution of sulfuric acid (H_2SO_4), and a 0.1 N solution of sodium hydroxide (NaOH) as well as sodium chloride (NaCl). Accurate pH levels were determined by using a numerical pH meter to ensure accurate monitoring and regulation throughout the experimental procedures.

3. RESULTS AND DISCUSSION

3.1. Impact from pH on copper removal efficiency

The initial pH of a solution exerts a profound influence on the efficacy of electrocoagulation treatment (ECT), a critical process in wastewater remediation. The removal efficiency of pollutants is intricately governed by the interrelationship between the concentration of hydrogen ions (H^+), the generation of coagulants during electrocoagulation, and the release of negatively charged ions from colloidal particles. These parameters synergistically determine the overall effectiveness of the ECT in wastewater treatment [64-65]. The pH predominantly affects the electrocoagulation mechanism by modulating the release of hydroxide ions from the coagulants, a factor that is indispensable for the successful removal of contaminants. However, at extended electrolysis durations, pH fluctuations become marginal, as the system naturally gravitates towards a neutral pH equilibrium. Additionally, an increase in current density promotes the electrolysis of water, resulting in a higher production of water molecules. Consequently, the rise in pH under these conditions becomes progressively less critical to the overall process efficiency [66].

$$H^{+}_{(aq)\ )} + OH^{-}_{(aq)} \rightarrow H_2O \qquad \textbf{Eq. 5}$$

The diagram in Figure 3 explains in detail by showing the effect of pH, treatment duration, and applied electric current on the copper concentration. The findings show that copper removal was highly efficient during the initial phase of the electrocoagulation process. Specifically, within 30 minutes of treatment, a removal efficiency of around 99% was reached when the process was carried out over the acidic pH from 3 to 5.

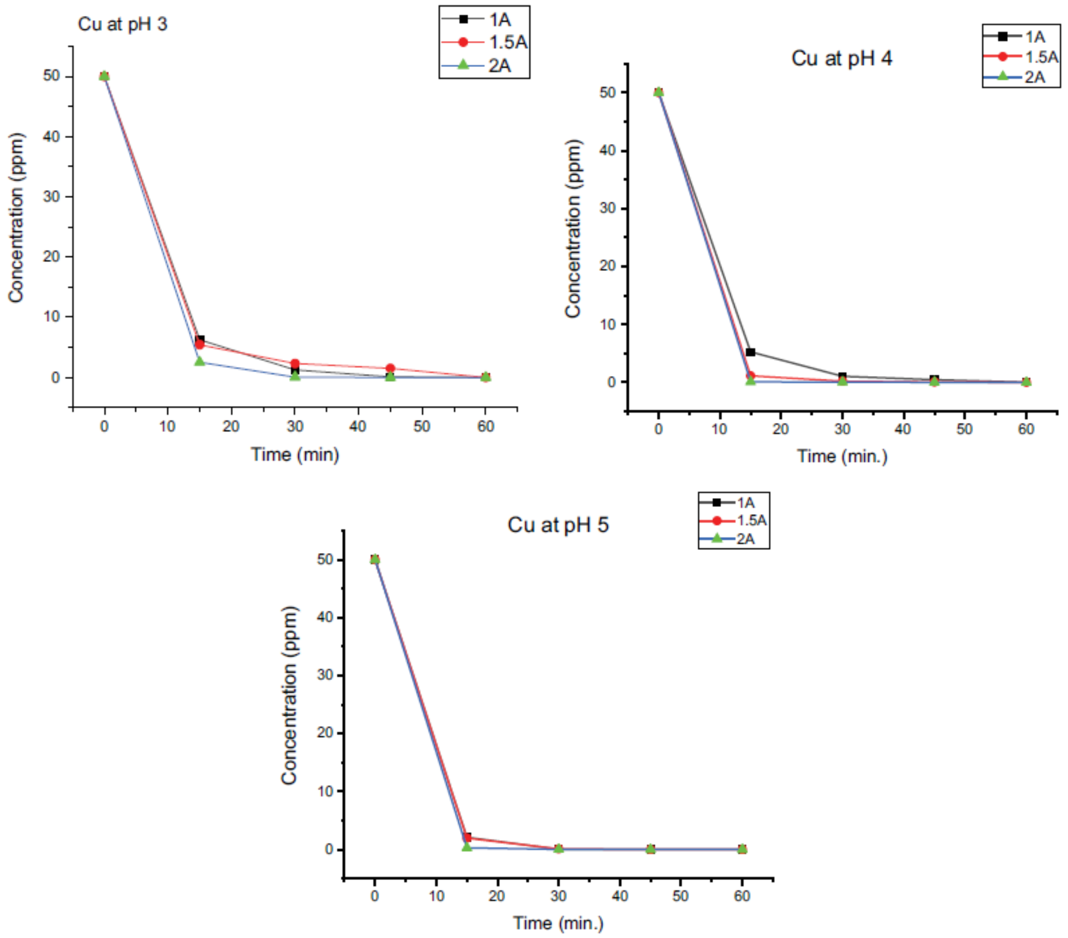

Figure 3. Variation in copper concentration with respect to different pH levels and current values

3.2. Impact of Current on Copper Removal

Electric current is a fundamental determinant of interaction rates within electrochemical systems, critically influencing aluminum ion production at the anode. As a key operational parameter in electrochemical cells (ECs), it is the primary variable that can be directly modulated. In these systems, the distance between electrodes is fixed, and current is continuously applied. The current density significantly impacts both the dosage of the coagulant and the rate of bubble generation, which in turn affect solution mixing and mass transfer processes at the electrodes[67]. Recent studies underscore the importance of optimizing current density to enhance efficiency in electrochemical systems. For instance, increasing the current density can improve the rate of aluminum ion production, but it also necessitates careful management to prevent undesirable side effects, such as excessive heat generation and electrode degradation [68]. Furthermore, the influence of current density on bubble formation is well-documented, with higher densities leading to increased bubble production, thereby enhancing turbulence and improving mass transfer rates [69].

The extent of metal dissolution or deposition is intrinsically linked to the quantity of electrical charge passing through the electrolytic medium. Higher current densities intensify the anodic dissolution process, leading to an increased formation of hydroxylated complexes, which in turn enhances the removal efficiency of pollutants. The generation of aluminum ions (Al^{3+}) from the electrodes is critically dependent on the applied current. Increased current densities result in a more pronounced anodic dissolution of aluminum, producing a larger volume of precipitates that are crucial for effective pollutant removal. Moreover, elevated current densities accelerate bubble nucleation rates while simultaneously reducing bubble size, which can further optimize pollutant removal by improving flotation and separation processes. This detailed reformulation emphasizes the electrochemical principles and mechanisms underlying pollutant removal, reflecting a higher level of scientific precision.

4. CONCLUSION

Pollution of aquatic systems by heavy metals is a major global environmental challenge, exacerbated by industrial effluents and subsequent leaching into groundwater. While some heavy metals are integral to biological processes, their elevated concentrations in aquatic environments pose significant risks to both ecosystems and human health. This paper demonstrates an effective electrocoagulation methodology for the removal of copper (Cu) from contaminated water. The research highlights that Cu removal efficiency increases with longer electrocoagulation times, higher NaCl concentrations, and greater applied electric currents. The optimal conditions identified—specifically, a pH of approximately 4, an applied electric current of 2 A, and an electrolysis duration of 60 minutes—offer a significant advancement in the effective management of copper contamination. These findings contribute to the broader understanding of electrocoagulation techniques and provide a foundation for future research aimed at improving water quality and mitigating heavy metal pollution.

Declarations of interest

The authors declare no conflict of interest in this reported work.

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