Anal. Bioanal. Electrochem., Vol. 16, No. 8, 2024, 737-751
https://www.doi.org/10.22034/abec.2024.715424

Analytical &
Bioanalytical
Electrochemistry

2024 by CEE
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Full Paper

Developing An Innovative Approach for Industrial Wastewater Treatment: Assessing the Effectiveness of Electrocoagulation in The Removal of Chromium VI from Electroplating

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Received: 9 April 2024 / Received in revised form: 17 July 2024 /
Accepted: 29 July 2024 / Published online: 31 August 2024

Abstract- Electrocoagulation has demonstrated its efficacy in treating industrial effluents by effectively removing pollutants, particularly metallic contaminants. The electrochemical processes occurring at aluminum electrodes have shown excellent performance in this regard. In this study, electrocoagulation experiments were conducted on an industrial effluent originating from an electroplating bath situated in Casablanca, Morocco. The primary objective was to eliminate chromium in the effluent and reuse the processed water for other applications within our facility. To achieve this goal, we systematically optimized various operational parameters influencing the electrocoagulation efficiency, including electrical voltage, electrode material, stirring speed, and electrode spacing. Additionally, we assessed their impact on pH, conductivity, and chromium concentration. The experiments were conducted in a well-mixed reactor using an industrial solution containing a high concentration of chromium, specifically 1 g/l of Cr (VI). The chromium removal efficiency was evaluated under specific operational conditions, including the use of aluminum electrodes, regulated voltages of 6 volts and 12 volts, an optimal stirring speed of 600 rpm, and an electrode spacing of 2 cm.

Keywords- Chromium; Electrocoagulation; Aluminium electrodes; Aluminium hydroxide; Wastewater; Removal

1. INTRODUCTION

The global demand for water is steadily rising, exacerbated by industrial activities, particularly those in surface treatment industries, which continue to discharge significant volumes of wastewater. Water pollution stems from various origins, but industrial water pollution stands out as a primary source, both in terms of volume and the severity of contaminants introduced into aquatic ecosystems. The contamination of wastewater generated by chemical industries poses severe environmental hazards. The deleterious effects extend beyond immediate concerns, impacting ecosystems and human health in multifaceted ways. To mitigate their adverse effects, a range of treatment methodologies is employed to address the detrimental impact of pollutants from industrial wastewater, particularly those from the chemical industry. Among these methods, physico-chemical techniques are commonly employed, with adsorption being a prominent approach [1], ion exchange [2], precipitation [3], reverse osmosis [4] and coagulation. Electrocoagulation technology utilizes the principles of coagulation and flocculation to facilitate wastewater treatment processes. This technique holds significant importance in the realm of wastewater treatment due to its efficacy in removing various contaminants through electrochemical reactions. Electrocoagulation technology offers a means to minimize emissions through water treatment processes. This method involves the application of an electric current to destabilize and remove contaminants from water by inducing coagulation and subsequent flocculation. By leveraging electrochemical reactions, electrocoagulation facilitates the removal of various pollutants, including suspended solids, heavy metals, and organic compounds, thereby contributing to the mitigation of environmental pollution [5], hydrocarbon spills [6], use of water loaded chromium [7,8] as well as metals like arsenic [9-11], copper, lead, cadmium [12], iron [13,14], the same applies to oil [15], to oxygen requirement [16,17], to color [18] and to organic compounds [19,20]. The contamination of water bodies by heavy metals, often referred to as trace metals, poses a significant and enduring environmental challenge. These metals are characterized by their stability and persistence, as they cannot be easily degraded or eliminated from the environment. Moreover, the majority of these metals exhibit toxic and carcinogenic properties, presenting serious risks to both human health and the ecosystem upon being discharged into water sources [21-23]. The management of water and wastewater containing heavy metals is a critical global concern that demands immediate attention. Various methodologies are employed to address the issue of heavy metal contamination. These techniques encompass various approaches designed to reduce the negative impacts of heavy metals on both the environment and human health [24-27].

Chromium is recognized as a toxic and carcinogenic heavy metal, distinguished by its non-biodegradable nature and propensity to bioaccumulate within living organisms. This element's environmental presence is of considerable concern, as it poses significant health hazards. Chromium exposure is associated with a myriad of disorders and illnesses, including but not limited to respiratory, renal, and dermatological conditions. Its classification among the sixteen most hazardous pollutants underscores its profound adverse effects on human health [28]. The pervasive presence of chromium in various environmental matrices, particularly aquatic systems, exacerbates the risk to human populations due to its inherent toxicity and carcinogenicity [29]. Copper, a prevalent heavy metal, is discharged into aquatic ecosystems by various industrial activities, including leather tanning, metal plating, pigment and ink manufacturing, wood treatment, and alloy production. Its impact on the environment, including its bioavailability and toxicity, varies depending on its oxidation state [30]. Hexavalent chromium Cr(VI) and trivalent chromium Cr(III) are distinguished as the predominant and most stable oxidation states of chromium in the environment. This distinction arises due to their relative stability and the specific chemical and physical processes that favor their persistence. Hexavalent chromium, in particular, is noted for its high solubility and mobility in water, which significantly impacts its environmental distribution and potential for bioavailability. Conversely, trivalent chromium is less soluble and tends to form stable complexes with organic matter and minerals, thereby influencing its geochemical behavior and environmental fate. The stability and prevalence of these oxidation states are key to understanding chromium's environmental chemistry and its ecological and health implications. These two forms of chromium are extensively distributed in various environmental compartments, including soil, water, and air, due to their industrial and natural sources [31]. Hexavalent chromium Cr(VI) compounds exhibit higher solubility and mobility in water compared to other forms of chromium [32]. The hexavalent chromium Cr(VI) forms are notably more hazardous, displaying higher toxicity, mutagenicity, carcinogenicity, and teratogenicity compared to chromium in its trivalent Cr(III) state.

Chromium is ubiquitous across various industrial sectors, playing a pivotal role in processes such as leather tanning, metallization, printed circuit board manufacturing, metallurgy, and metal finishing. Its widespread use in these applications highlights its significance as a versatile element in industrial operations [33-37]. In aqueous systems, chromium typically exists in two main forms: trivalent Cr(III) and hexavalent Cr(VI). These two forms exhibit distinct chemical behaviors, bioavailability, and toxicity levels. Hexavalent chromium, denoted as Cr(VI), is particularly notorious for its toxicity to various life forms, including humans, animals, plants, and microorganisms. Chromium in its hexavalent form is not only carcinogenic but also exhibits high solubility in aqueous environments [38-41]. Conversely, trivalent chromium Cr(III) exhibits significantly lower toxicity compared to hexavalent chromium Cr(VI). It possesses low solubility in aqueous solutions and readily precipitates as $Cr(OH)_3$ when the pH level reaches 4.0 or higher [42- 44]. Hence, the reduction of chromium holds paramount significance, as it transforms the highly toxic and mobile Cr(VI) species into the less harmful and immobile Cr(III) form [45]. Indeed, there are ongoing initiatives aimed at exploring the application of electrocoagulation technology for the treatment of industrial wastewater containing hexavalent chromium ions. This process involves the use of electrical charges to destabilize and remove contaminants from water, offering a promising solution for addressing the challenge of chromium pollution in industrial effluents. This method initiates the production of essential reagents in solution through oxidation induced by an electrode, specifically the anode. Nonetheless, its efficacy is primarily constrained by the magnitude of the direct current applied and the operational lifespan of the electrode. Previous studies have suggested that the electrocoagulation process holds promise for the removal of suspended solids from aqueous solutions [46], heavy metals [47], petroleum [48], colorants [49], water-based manure [50], fluoride waters [51], as well as urban wastewater [52]. In the last two decades, its applications expanded significantly, and electrocoagulation is today the subject of great attention for treating a wide range of effluents containing metals, foodstuffs, olive oil, textile colorants, fluorine, polymer wastes, organic matter from waste landfill sludge, turbidity, chemical and mechanical polishing wastes, aqueous suspensions of ultrafine particles, nitrates, phenolic wastes and arsenic in addition to municipal wastewater [53,54].

Electrocoagulation, a multifaceted process, encompasses a plethora of physical and chemical reactions, culminating in its efficacy. Its performance is contingent upon the interplay of electrochemical and physico-chemical parameters. A diverse array of technologies is currently employed to address the removal of toxic metals, either individually or in tandem, from wastewater [55,56], including nanofiltration [57], adsorption [58], bio-remediation [59], surface flocculation [60], electroless precipitation [61], reverse ion exchange [62], nano-materials [63], as well as microbial electrolyte cells [64]. Moreover, several electrochemical methodologies have been implemented for the treatment of metallic wastewater, including electro-oxidation techniques [65], electroperoxone [66], electroflotation [67], electrodeposition [68], electrofloccu-ation and electro-reduction [69], electrocoagulation and adsorption, and peroxi-coagulation [70]. Electrochemical technologies offer promising solutions for addressing the challenges associated with traditional treatment methods in removing heavy metals from wastewater originating from diverse sources. These innovative approaches leverage electrochemical processes to achieve efficient and effective removal of heavy metal contaminants [71].

The current manuscript delineates the apparatus and methodologies employed in our experimental trials. It intricately details the analytical procedures and instruments utilized for evaluating the outcomes of the conducted processes. The study will delve into the impact of several parameters, notably the current density criterion, pH levels, conductivity, initial concentration of pollutants, treatment duration, sampling techniques, and electrode configuration, on the effectiveness of the electrochemical process for removing Cr(VI) from wastewater. The primary aim of this research is to conduct an in-depth analysis of certain physico-chemical parameters under the influence of different electrical voltages, specifically 6V and 12V. Furthermore, this study seeks to evaluate the immediate effects of electric current on the electrocoagulation process, particularly in the context of treating wastewater contaminated with hexavalent chromium ions. This comprehensive examination is intended to elucidate the underlying mechanisms and efficiency of electrocoagulation under varying electrical conditions, thereby contributing to the optimization of this treatment method for industrial wastewater applications.

2. METHODOLOGY

2.1. The electrocoagulation theory

The process of electrocoagulation, initially devised and patented in 1906 by Dietrich for the purification of bilge water in ships, operates on the principle of employing soluble anodes. This technique involves the dissolution of these anodes, which facilitates the removal of contaminants through electrochemical reactions, thereby enhancing the overall quality of the treated water [72]. This technique involves the passage of an electric current through two aluminum electrodes submerged in an electrolytic bath within a reactor. This current initiates the formation of $Al^{3+}(aq)$ ions, which act as coagulation agents in the solution, facilitating the flocculation and coagulation of the targeted pollutants. Through electrolysis, dissolved, oxide-like, or reducible substances present in the effluent can also be coagulated. The application of an electric field facilitates the migration of ions and charged particles, leading to the aggregation of suspended particles into flocs. These flocs can then be removed through conventional material processes such as settling, flotation, or filtration [73]. Figure 1 depicts the operational mechanism of the electrocoagulation process employing aluminum plates.

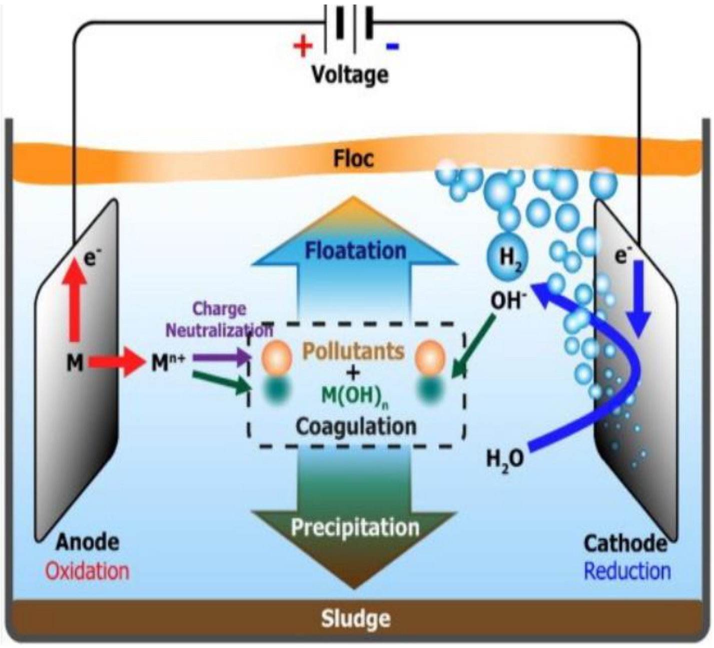

Figure 1. Operating principle of electrocoagulation [74]

2.2. Electrode reactions

Electrocoagulation is a process that entails the utilization of a direct current, generated externally, which is applied between two electrodes. This method involves the passage of an electrical current through a conductive medium, typically a liquid solution containing contaminants or impurities. The electrodes serve as conduits for the flow of electricity, leading to the destabilization and subsequent removal of pollutants through coagulation and precipitation processes [75]. This process initiates several reactions, as demonstrated by various studies [76-78].

- ✓ Water reduction at cathode : $6\ H_2O_{(liq)} + 6e^- \rightarrow 3H_{2(g)} + 6\ OH^-_{(aq)}$ Eqn. 1
- ✓ Formation of Al^{3+}(aq) ions at the anode : $2Al_{(s)} \rightarrow 2Al^{3+}_{(aq)} + 6e^-$ Eqn. 2

At the appropriate pH level, the two species undergo a chemical reaction to produce the compound $Al(OH)_3$(s), as depicted by the following equation:

$$Al^{3+}_{(aq)} + 3OH^-_{(aq)} \leftrightarrow Al(OH)_{3(s)} \qquad \text{Eqn. 3}$$

This reaction denotes the precipitation of aluminum hydroxide, a pivotal process influencing diverse applications, notably in coagulation-flocculation within water treatment systems. Aluminum hydroxide precipitate, formed as a result, assumes a critical function by facilitating the aggregation and removal of contaminants through the formation of larger, easily separable flocs, thereby enhancing the efficiency of purification processes in aqueous environments.

2.3. The hexavalent chromium ion solution used in this study

To perform the electrocoagulation experiments, a solution containing hexavalent chromium at an initial concentration of C_0 = 1 g/l is prepared. This is achieved by dissolving 1 gram of hexavalent chromium in 1 liter of distilled water. Subsequently, the solution is agitated for 5 minutes to ensure homogeneity and adequate dispersion of the chromium ions throughout the solution.

Experimental trials were conducted employing the electrocoagulation technique on a solution containing hexavalent chromium ions at a concentration of 1g/l. The setup involved the utilization of two aluminum electrodes submerged within a specific volume of the solution. The dimensions of the electrodes were precisely defined as follows: each electrode measured 8.1 cm in length, 2.1 cm in width, and 1 mm in thickness, providing an active surface area of 17.01 cm². The electrodes were positioned at a separation distance of 2 cm from each other.

The hexavalent chromium ions in the solution are subjected to agitation at a speed of 600 revolutions per minute (rpm) using a magnetic stir bar positioned at the base of the electrolysis cell (refer to Figure 2). This stirring action is intended to promote uniform mixing and enhance the contact between the chromium ions and the electrolyte solution, facilitating effective electrochemical processes. The stirring process is crucial for achieving an optimal dispersion of aluminum ions (Al^{3+}) and hydroxide ions (OH^-) throughout the solution. This ensures thorough mixing and enhances the uniform distribution of reactants, facilitating effective chemical reactions and the formation of desired products. Stirring also promotes mass transfer by reducing concentration gradients, thereby improving reaction kinetics and overall efficiency. The agitation intensity is meticulously regulated to ensure effective mixing without compromising the integrity of the flocs. This balancing act is crucial to prevent excessive shear forces that could lead to the disintegration or breakage of the formed flocs. Adjusting the agitation intensity optimally facilitates thorough dispersion of particles or substances in the solution, promoting homogeneity without adversely affecting the stability and effectiveness of the floc structure [79].

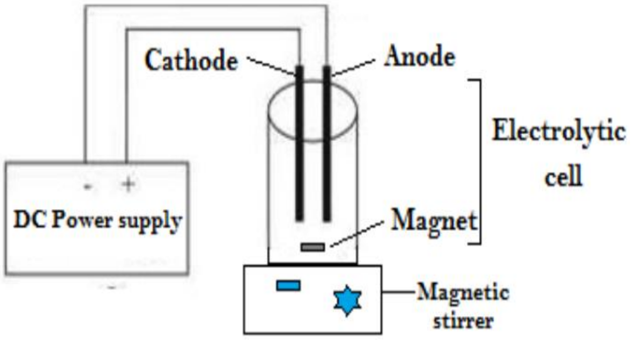

Figure 2. Experimental reactor used for electrocoagulation

3. RESULTS AND DISCUSSION

In the course of experimentation, a comprehensive set of parameters is gauged, encompassing pH levels, electrical conductivity, and temperature variations (Table 1).

Table 1. Evolution of measured parameters over time

U = 6 V / C=1000 mg/l						
Time (min)	0	4	8	12	16	20
pH	4.38	4.41	4.51	4.54	4.55	4.69
Cd (µS/cm)	8.76	8.80	8.84	8,87	8,86	8,85
Temperature (°C)	21.30	22.20	22.30	22.39	22.40	22.60
U = 12 V / C=1000 mg/l						
Time (min)	0	4	8	12	16	20
pH	4.33	4.56	4.66	4.75	4.79	4.97
Cd(µS/cm)	08.76	08.81	8.82	8,91	8,87	8,86
Temperature (°C)	21.30	22.30	22.34	22.40	22.75	22.80

During the electrocoagulation process, the pH of the solution undergoes continuous fluctuations instead of staying constant. This variability is driven by various factors intrinsic to the process, including the production of hydrogen and hydroxide ions at the electrodes, alongside the concurrent precipitation of metal hydroxides or oxides. These reactions are responsive to changes in current density, electrolyte concentration, and the composition of the treated water. The fluctuating pH levels play a crucial role as they impact the effectiveness and reliability of electrocoagulation in wastewater treatment by influencing the precipitation and elimination of contaminants. These fluctuations occur as a result of various factors such as the introduction of electrical currents, the interaction of ions with the solution, and the formation of different chemical species. As the process unfolds, these fluctuations in pH dynamics critically influence the efficiency and efficacy of electrocoagulation in wastewater treatment or solution purification. These changes can significantly affect the electrochemical reactions occurring at the electrodes, altering the precipitation and removal of contaminants. Understanding and controlling pH variations are therefore essential for optimizing electrocoagulation processes to achieve desired water treatment outcomes effectively. Figure 3 illustrates the fluctuation of pH over time in correlation with the applied electrode voltage.

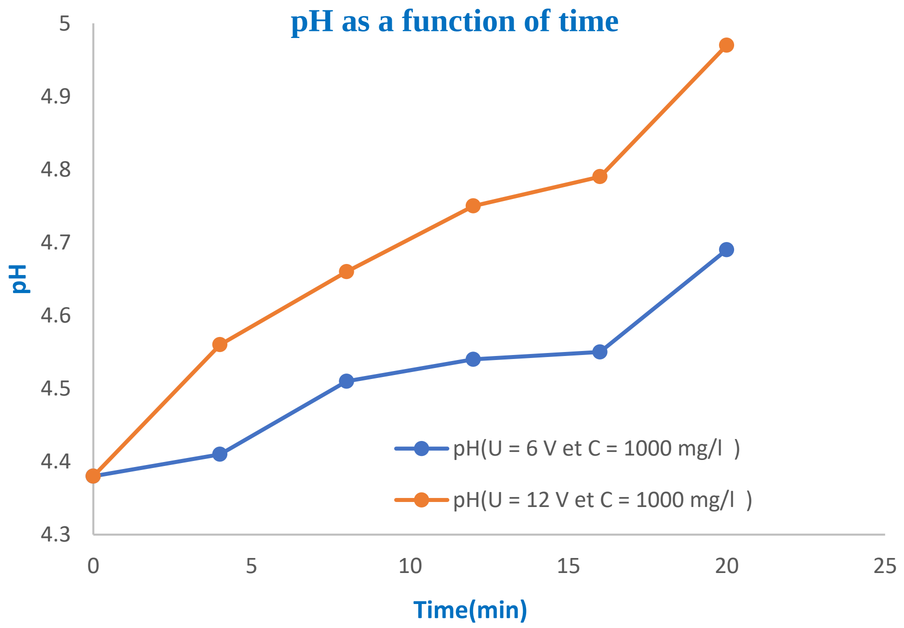

Figure 3. Changes in measured pH over time

The initial pH level is universally recognized as a vital parameter in electrocoagulation processes. It significantly influences the efficiency and performance of electrocoagulation systems by affecting various critical aspects. Firstly, the pH determines the speciation of ions, which is essential for the proper functioning of the electrochemical reactions. Secondly, it impacts the formation of coagulants, the substances that aggregate particles and impurities, facilitating their removal. Lastly, the pH plays a key role in the overall electrochemical reactions involved in the process, dictating the effectiveness of contaminant removal and the stability of the system. Thus, maintaining an optimal pH level is crucial for the success of electrocoagulation treatments [80,81]. The observed advancement during the treatment process is closely connected to the effectiveness of the treatment itself. This progress reflects the extent to which pollutants are being effectively removed or mitigated from the system, serving as an indicator of the efficiency and functionality of the employed treatment method. This means that the degree of improvement seen in the treatment process directly correlates with how well the treatment method is working to eliminate or reduce contaminants, highlighting the overall performance and success of the treatment approach [82]. The process is significantly improved by the generation of hydroxide ions (OH^-) at the cathode electrode. This increase in pH levels creates a more alkaline environment, which facilitates the subsequent precipitation of pollutants from the solution. At elevated pH levels, a variety of dissolved contaminants undergo precipitation, transforming into solid forms that can be more readily separated and removed from the wastewater stream. This phenomenon is pivotal in wastewater treatment processes, where adjusting pH plays a critical role in enhancing the efficiency of contaminant removal through precipitation and subsequent filtration or sedimentation processes. This mechanism not only enhances the overall efficiency of the purification process but also ensures a more effective elimination of harmful substances [83,84].

Figure 4 provides a detailed illustration of how the conductivity changes over the entire duration of the experiment. The graph captures the fluctuations and trends in conductivity at various time points, offering a comprehensive view of the temporal variation observed throughout the study.

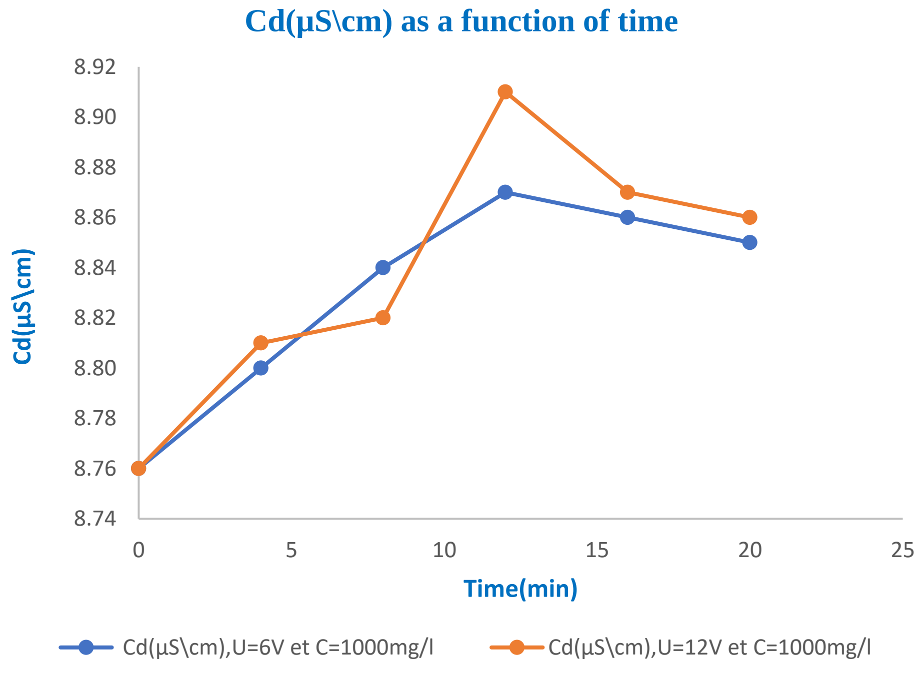

Figure 4. Changes in measured conductivity over time

At the initiation of the electrocoagulation process, a potential disparity arises between the electrodes, leading to the generation of metallic coagulants. This phenomenon triggers electrochemical reactions at the electrodes' surfaces, culminating in the production of species such as metal hydroxides or oxyhydroxides. These species serve as effective coagulants, aiding in the removal of contaminants from the water through processes like adsorption, precipitation, and flocculation. Metal coagulants are introduced into the solution where they disperse and initiate reactions with ions, notably chromate ions. These reactions instigate the formation of flocs, which are conglomerates of suspended particles capable of entrapping various substances, including chromate ions. As the chromate concentration diminishes over time during the electrocoagulation process, the conductivity of the solution may gradually decline. This decline is attributed to the removal of ions from the solution as they undergo coagulation and precipitation. The formed flocs, comprising the coagulated contaminants, eventually separate from the treated solution. These flocs can then be effectively removed from the solution using various separation techniques such as filtration or decantation [85].

After the removal of flocs, additional steps can be taken to further decrease the solution's conductivity. These steps usually include methods like ion exchange, membrane filtration, or chemical precipitation, which specifically target residual ions or contaminants that contribute to electrical conductivity. The selection of each method depends on its efficacy in addressing particular water chemistry conditions and achieving the desired level of conductivity reduction. This approach ensures that the treated solution meets conductivity standards appropriate for a range of industrial, environmental, or potable water uses.

Figure 5 illustrates the variation in reactor temperature over time for different applied voltages, specifically 6 V and 12 V. This comparison allows for the observation of how changes in voltage affect the temperature dynamics within the reactor system.

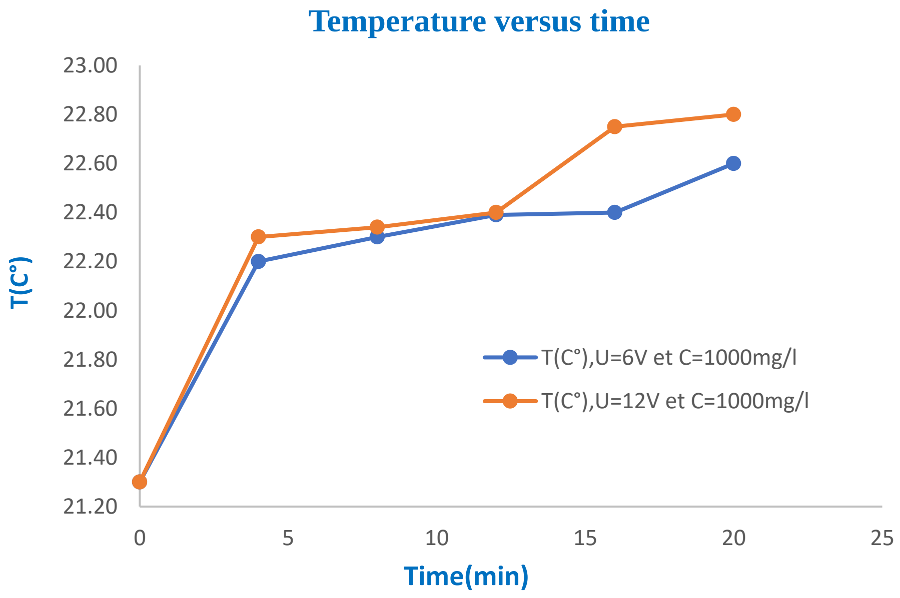

Figure 5. Changes in measured temperature over time

During the process of electrocoagulation, the application of an electric current generates a significant amount of heat. This heat causes contaminants in the water to coagulate, or clump together, making it easier to remove undesirable particles. The electric current facilitates the destabilization of suspended particles, dissolved metals, and other pollutants, leading to their aggregation and subsequent removal from the solution. This process effectively purifies the water by targeting and eliminating various contaminants through thermal and electrochemical reactions. As the electric current flows through the solution, it generates heat, leading to a noticeable rise in temperature. The temperature elevation significantly enhances the efficiency of the electrocoagulation process by accelerating the aggregation of impurities. This phenomenon promotes the rapid clumping of contaminants, facilitating their more efficient removal from the water. As a result, the process yields a cleaner and more purified water output due to enhanced aggregation kinetics under elevated temperatures.

4. CONCLUSION

This study focuses on the electrocoagulation-based removal of chromium from wastewater within a batch-operated system. The study aims to optimize various operational parameters influencing the efficiency of electrocoagulation. These parameters include electrical voltage, electrode material, agitation speed, and electrode spacing. Additionally, the study evaluates their impact on pH, conductivity, and chromium concentration in the wastewater. Chromium removal efficiency is assessed under specific operating conditions, which involve the use of aluminum electrodes, regulated voltages of 6 volts and 12 volts, an optimal stirring speed of 600 rpm, and an electrode spacing of 2 cm.

Author Declarations

- Consent for publication

  All authors have read and agreed to the published version of the manuscript .
- Funding

  The authors did not receive support from any organization for the submitted work .
- Competing interests

  The authors declare they have no conflict of interest .
- Data Availability

  The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request. The authors declare no conflict of interest in this reported work.

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