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Original Research

Evaluation of Electrocoagulation Efficiency in Domestic Wastewater Treatment Under the Influence of Operational Parameters

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ABSTRACT

Domestic wastewater is one of the biggest problems facing the environment, being one of the most important sources of environmental pollution. It changes the physical and biological properties of the environment when discharged without treatment. The removal of pollutants from industrial and domestic wastewater using electrocoagulation (EC) technology was investigated. This study aimed to evaluate the effects of several operating parameters on pollutant removal efficiency. These parameters included applied voltage, flow rate, electrode spacing, NH_4Cl concentration, and reaction time. A stainless-steel electrochemical cell, consisting of both a cathode and an anode, was constructed for the experiments. The effect of each variable was examined independently. The results showed that under optimal conditions of electrode spacing of 1 cm, a flow rate of 0.05 L/min, an NH_4Cl concentration of 300 mg/L, an applied voltage of 15 V, and a hydraulic retention time of 45 minutes, the highest pollutant removal efficiencies were achieved: 83% for turbidity, 85% for TSS, 84% for COD, and 82% for BOD. Conversely, at non-ideal conditions (9 cm electrode spacing, 3 V voltage, and 15 min holding time), the removal effectiveness fell markedly to less than 50%. The findings indicate that the electrocoagulation process is a sure method of removing pollutants in wastewater, provided that it takes place under appropriate conditions. It improves the quality of the water by eliminating pollutants.

Keywords: Domestic wastewater, Electrocoagulation, Electrodes, Hydraulic retention time, Stainless steel

1. Introduction

Untreated wastewater from homes is one of the biggest environmental problems because it changes the physical and biological features of the receiving area and is thought to be a major source of pollution [1]. Domestic wastewater in 2022 included water used for bathing, washing, cleaning, cooking, and doing laundry. Along with other substances that might harm both the environment and human health, it contains soap, detergents, and other agents [2]. Increased industrialization, population growth, and overuse of water resources are among the most important factors that have led to pollution and water scarcity becoming two growing global problems. In 2020, only 74% of the world's population, or approximately 5.8 billion people, had access to drinking water services [3, 4]. Electrolysis combines the benefits of coagulation, sedimentation, and electrochemistry into a single system [5, 6]. Two types of physical, chemical, and electrical processes work together in electrocoagulation (EC) to clean up wastewater. Applying an electric current to oxidize electrodes makes metal ions dissolve in the same position where they are inserted. Electrode dissolution produces coagulants, which attach to contaminants, clump them into suspended particles, and then sediment and filter them out of the wastewater [7]. In 1946, in the United States, electrocoagulation was first employed on a large scale to treat the drinking water [8, 9]. At that time, neither electrical nor electrochemical water treatment technologies were widely used around the world because they were expensive to set up. However, these technologies owe a great deal to the groundwork that was laid by rigorous research in the United States and the former Union of Soviet Socialist Republics, spurred on by tougher environmental and drinking water regulations. Low cost coupled with high efficiency has renewed electrochemical water treatment technologies over the past 20 years. Such treatments are currently required, primarily to treat wastewater containing contaminants that are non-destructible by thermal means [10]. Treatment by EC has also recently resurfaced, thanks to its prospects of integrating benefits from both methods of electrochemical treatment as well as normal methods of coagulation [11]. The principle of EC involves electrically dissolving electrodes to form soluble or insoluble species that facilitate the coagulation and sedimentation of suspended pollutants in domestic wastewater, whether in continuous or batch operation modes [12]. During EC, electrochemical reactions typically occur using iron or aluminum electrodes. At the cathode, water undergoes reduction, while at the anode, the metal dissolves - a reaction known as the anodic process [13]. EC presents an alternative to the use of chemical coagulants such as polymers or mineral salts. It enhances the destabilization of emulsions and suspended particles through the formation of charged metal hydroxides in the aqueous phase. These hydroxides neutralize the electrostatic charges of suspended solids and oils, promoting coagulation and the precipitation of metals and salts [14]. Key factors influencing the efficiency of the EC process include the type of electrodes used and the duration of the current application [15]. With the increasing population growth and environmental impacts, the treatment of domestic wastewater has become a priority, as it contains many pollutants such as COD, TSS, TDS, turbidity, and BOD that affect water quality [16]. The EC process has proven its high efficiency in removing pollutants due to its low operating cost and the small amount of sludge produced compared to traditional treatments. A study by El-Azazy et al. (2022) [17] showed that the removal rate of COD and turbidity reached 95% and 83%, respectively, at operating conditions of 15 volts, pH = 7, and an operating time of 60 minutes. Another study (Wahid et al., 2023) [18] also mentioned the use of stainless steel electrodes to remove pollutants from domestic wastewater, where the removal rate of COD and turbidity reached 91% and 95%, respectively, at an operating time of 15 minutes and a low current. Another study in MDPI (Mao et al., 2023) [19] also showed the use of stainless steel electrodes in the EC process. It resulted in the removal of more than 90% of each of TSS, TDS, and BOD with a significant reduction in operating cost at 20 volts and 45 minutes. In another study conducted by Gao et al. (2021) [20], raising the applied voltage to the range of 20-15 volts with a moderate current achieves high removal of each of TSS and TDS without an excessive increase in energy consumption. In another study published in the journal Sustainable Engineering and Technology (2024) [21], the effect of operating factors such as time, voltage, current, and concentration of primary pollutants on removal efficiency was analyzed. It was concluded that this technology is very effective with water with high organic matter. These combined studies confirm that EC is an effective and successful method for removing organic and inorganic pollutants from domestic wastewater and open up prospects for its application in communities with low and limited resources due to its simplicity and low operating cost.

2. Methodology (continuous study)

The EC system was constructed using Perspex glass with dimensions of 40 cm (length) × 25 cm (width) × 15 cm (height) to carry out domestic wastewater treatment experiments. Five pairs of stainless-steel plates, each with an active surface area of 140 cm², were used as both cathodes and anodes. The electrodes were spaced 1 cm apart and positioned 1 cm above the bottom of the EC cell. After preparing the artificial wastewater, it was pumped from a feed tank into the electrocoagulation cell at a suitable flow rate. The experiments were conducted in sequential stages, with one variable altered in each stage, as shown in Table 1. The optimal value obtained from each stage was applied in the subsequent stage. Treated water was collected in an external tank, and samples were taken from the tank outlet every 15 minutes over a total period of 75 minutes. However, the effective reaction time for all experiments was fixed at 45 minutes. A magnetic stirrer operating at 140 rpm was used throughout the process to ensure proper mixing of the coagulated solution. All experiments were conducted at room temperature (24°C). At the end of each experiment, the power supply was turned off, and the electrodes were cleaned using a dilute hydrochloric acid solution to prevent passivation. Using a continuous-flow EC reactor, this study found the conditions with the highest removal efficiency and eliminated pollutants from the domestic wastewater. Comparing pollution concentrations before and after treatment allowed one to estimate the removal efficiency using the following equation:

$$\eta\% = \left(\frac{C_0 - C_f}{C_0}\right) \times 100\%$$

Where C_0 is the initial concentration of the pollutant, C_f is the final concentration after treatment, and $\eta\%$ is the removal efficiency.

Table 1. Operating Conditions of Experimental Work

Effect	Flow (L/min)	Distance (cm)	NH_4Cl (ppm)	Voltage (v)
Flow (L/min)	0.05, 0.10, 0.15	1	100	3
Distance (cm)	0.05	1, 3, 5, 7, 9	100	3
NH_4Cl (ppm)	0.05	1	0, 100, 200, 300	3
Voltage (v)	0.05	1	300	3, 6, 9, 12, 15

3. Results and discussion

This section illustrates and describes the results of tests conducted to utilize electrocoagulation for treating wastewater from residential homes. Determining how effectively pollutants are removed requires consideration of several operational parameters, including electrode spacing, electrolyte concentration, applied voltage, reaction time, and flow rate. This study found that, in order to utilize EC for removing pollutants from residential wastewater, electrodes should be separated by 1 cm, NH_4Cl concentration should be 300 mg/L, voltage should be 15 volts, flow rate should be 0.05 L/min, and reaction time should be 45 minutes. The optimal rates of chemical oxygen demand (COD), turbidity, biological oxygen demand (BOD), and total suspended solids (TSS) removal were achieved in these operating conditions, as shown in Table 2.

Table 2. Optimal Operating Conditions That Achieve the Highest Pollutant Removal Efficiency

	Raw water	Treated water	Removal %
Turbidity	100	45	85%
TSS	200	85	83%
COD	320	146	81%
BOD	140	62	82%

3.1. Effect of electrode spacing on pollutant removal efficiency

In this work, several electrode spacings were used in (EC) experiments to assess their effects on the pollutant removal from household wastewater. The tested spacings were 1, 3, 5, 7, and 9 cm. The results demonstrated that removal efficiency decreased with increasing electrode spacing. Fig. 1 illustrates the effect of electrode spacing on pollutant removal under specific operating conditions: pH = 7, NH_4Cl concentration = 100 mg/L, applied voltage = 15 V, and a fixed reaction time of 45 minutes. The highest removal efficiencies were achieved at an electrode spacing of 1 cm, where turbidity, TSS, COD, and BOD removal rates reached 60%, 63%, 60%, and 61%, respectively. When the spacing increased to 9 cm, the removal efficiencies dropped to 40% for turbidity, 44% for TSS, 49% for COD, and 36% for BOD. These results highlight how important it is to optimize electrode spacing to improve the performance of the EC process. Electrical conductivity goes down as the distance between electrodes increases. When the applied voltage stays the same, more space between the electrodes causes more electrical resistance, which reduces current density and, as a result, the efficiency of removing pollutants.

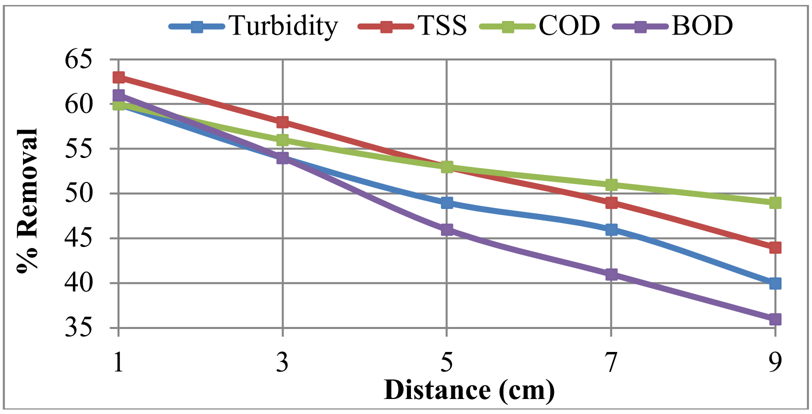

Figure 1. Effect of Electrode Spacing on Removal Efficiency

3.2. Effect of ammonium chloride (NH_4Cl) on pollutant removal efficiency

This study was to investigate the effect of ammonium chloride (NH_4Cl) concentration on the efficiency of electrocoagulation in treating domestic wastewater. Four NH_4Cl concentrations were tested: 0, 100, 200, and 300 mg/L. The experiments were conducted under constant operating conditions: pH = 7, applied voltage = 15 V, electrode spacing = 1 cm, flow rate = 0.05 L/min, and a fixed operating time of 45 minutes. The results, as illustrated in Fig. 2, showed that increasing the NH_4Cl concentration up to 300 mg/L enhanced the removal efficiency. At this concentration, the highest removal rates were recorded for turbidity, TSS, COD, and BOD, reaching 85%, 83%, 81%, and 87%, respectively. This improvement is attributed to the increased conductivity of the solution with higher electrolyte concentration, which reduces electrical resistance and increases current flow. It was, therefore, found that more metal ions and hydroxyl ions were produced, enhancing coagulation and pollutant removal. On the contrary, when no NH_4Cl was added (0 mg/L), a significant reduction in removal efficiency was noted, where turbidity, TSS, COD, and BOD removal percentages were reduced to 79%, 79%, 78%, and 81%, respectively. These findings indicate how significant the nature of electrolytes and their concentration are in determining how conductive the electrolyte solution can be. Some of these common electrolytes used in electrolysis include potassium chloride, ammonium chloride, and sodium chloride.

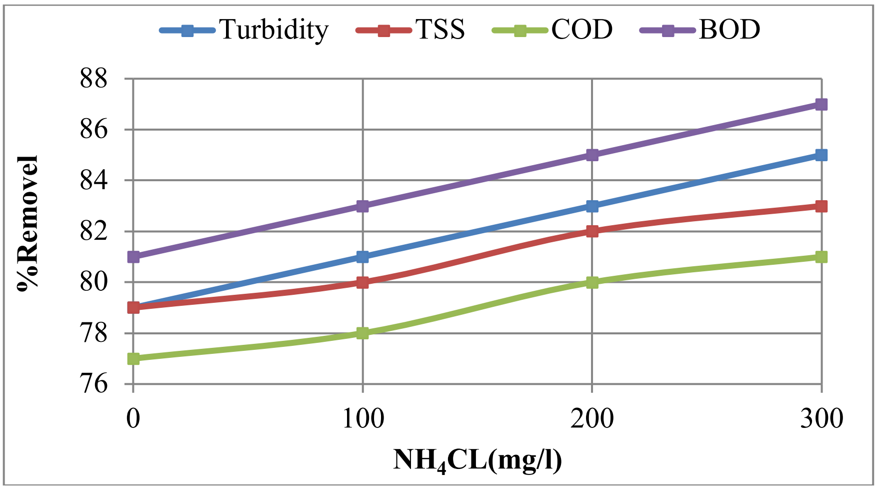

Figure 2. Effect of Ammonium Chloride (NH_4Cl) on Removal Efficiency

3.3. Effect of applied voltage on pollutant removal efficiency

This study operated the EC system with a DC power supply with a voltage range of 0–60 V and a current capacity of up to 15 A. Among the main factors affecting the efficiency of pollutant removal in the EC process is the applied voltage. Five voltage levels were tested: 3, 6, 9, 12, and 15 volts. The experiments were conducted under fixed operating conditions: pH = 7, NH_4Cl concentration = 300 mg/L, electrode spacing = 1 cm, and an operating time of 45 minutes. Fig. 3 presents the relationship between applied voltage and pollutant removal efficiency. The results indicated that increasing the applied voltage improved removal efficiency. At 15 V, the removal rates for turbidity, TSS, COD, and BOD reached 72%, 73%, 70%, and 71%, respectively. In contrast, at the lowest tested voltage of 3 V, the removal rates decreased to 55%, 58%, 54%, and 56%, respectively. This improvement in performance with increased voltage is attributed to enhanced generation of gas bubbles and coagulant species, as well as improved mass transfer at the electrode surface. At lower voltages, the generation of these species is reduced, which limits the efficiency of the EC process.

3.4. Effect of Electrolysis Time on Pollutant Removal Efficiency

The duration of the electrolytic reaction is a fundamental factor that directly influences the number of dissolved ions, the dosage of the coagulant, and the overall pollutant removal efficiency. In this study, electrolysis times of 15, 30, 45, 60, and 75 minutes were tested. The results, illustrated in Fig. 4, showed that increasing the reaction time improved removal efficiency. At 75 minutes, the removal rates of turbidity, TSS, COD, and BOD reached 83%, 83%, 84%, and 84%, respectively. However, at a shorter reaction time of 15 minutes, the removal rates decreased to 72%, 73%, 70%, and 71%, respectively. Despite the slightly higher removal efficiency at 75 minutes, the difference compared to 45 minutes was only about 5%. Therefore, 45 minutes was selected as the optimal reaction time, as it offers a balanced trade-off between efficiency, energy consumption, and operational time, especially when considering practical, real-world applications. The observed improvement with longer durations is attributed to the increased generation of coagulants from dissolved ions, leading to the formation of metal hydroxide flocs that effectively capture and remove pollutants at a constant current density. However, after a certain point, removal efficiency reaches a plateau, emphasizing the importance of identifying the optimal electrolysis duration to ensure effective and economical treatment.

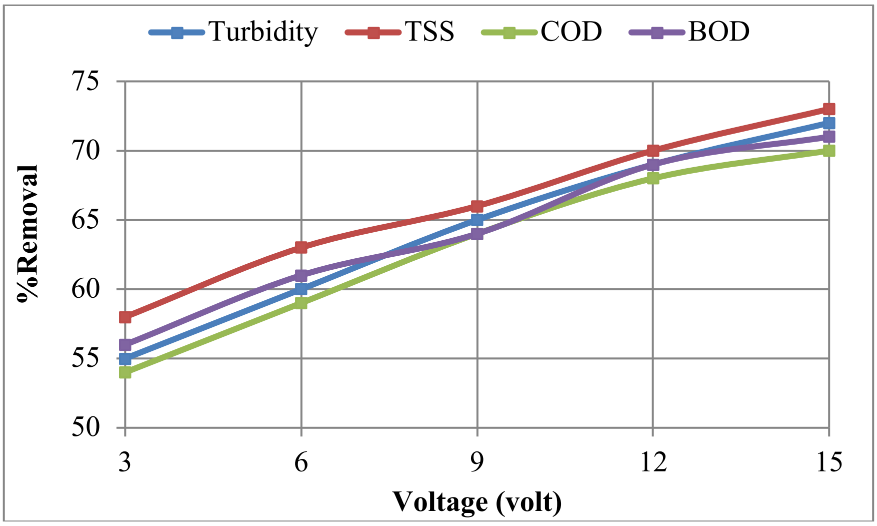

Figure 3. Effect of Applied Voltage on Removal Efficiency

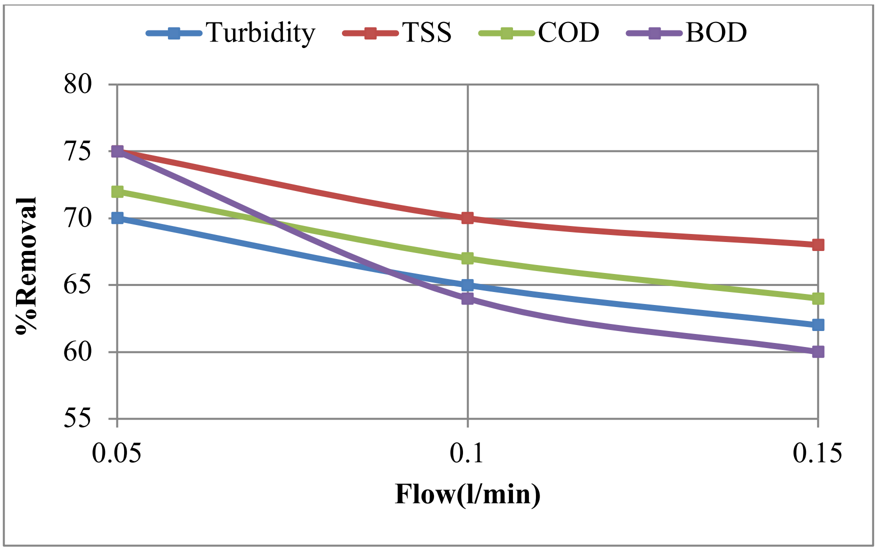

Figure 4. Effect of Electrolysis Time on Removal Efficiency

3.5. Effect of flow rate on pollutant removal efficiency

The impact of flow rate on the efficiency of pollutant removal from domestic wastewater was investigated by testing three different flow rates: 0.05, 0.1, and 0.15 liters per minute. The experiments were carried out under constant operating conditions: pH = 7, electrode spacing = 1 cm, applied voltage = 15 V, and a reaction time of 45 minutes. Fig. 5 illustrates the relationship between flow rate and removal efficiency. The results revealed that lower flow rates enhanced pollutant removal. At a flow rate of 0.05 L/min, the removal efficiencies for turbidity, TSS, COD, and BOD reached 70%, 75%, 72%, and 75%, respectively. In contrast, increasing the flow to 0.15 L/min led to a decline in removal efficiency, with corresponding values of 62%, 68%, 64%, and 60%, respectively. This decrease in performance at higher flow rates is attributed to the possible resuspension of settled particles, which increases turbidity and reduces treatment efficiency. Therefore, low to moderate flow rates are generally more effective, as they ensure adequate residence time and allow proper contact between pollutants and coagulants without disturbing settled materials.

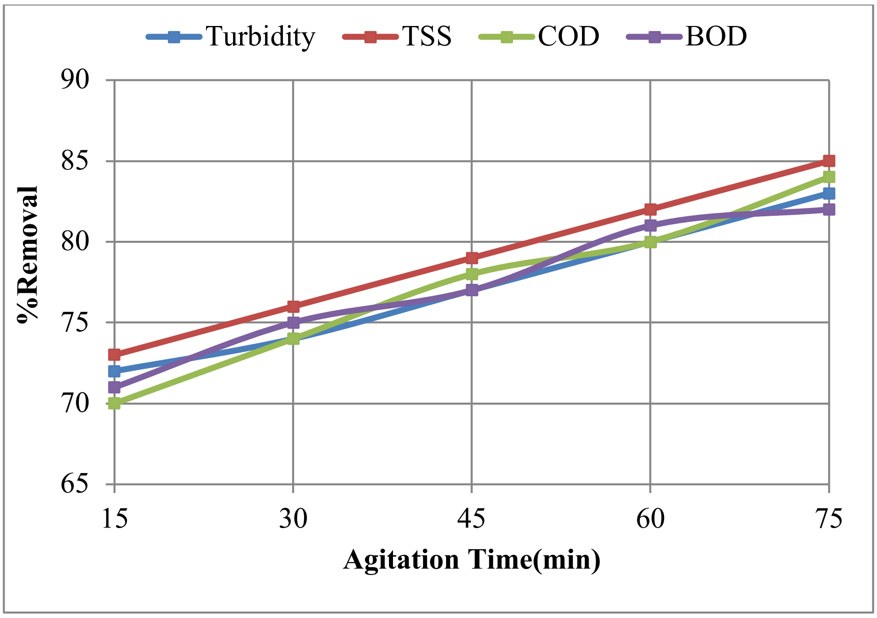

Figure 5. Effect of Flow Rate on Removal Efficiency

4. Conclusions

Experimental results demonstrated that electrocoagulation using stainless steel electrodes is an effective technique for removing pollutants from domestic wastewater. In this process, optimizing operational parameters plays a crucial role in enhancing removal efficiency, as these variables significantly impact the overall treatment performance. The highest removal efficiencies recorded for turbidity, TSS, COD, and BOD were 83%, 85%, 84%, and 82%, respectively. These optimal results were achieved under conditions of low flow rate, minimal electrode spacing, high ammonium chloride concentration, and increased applied voltage. In conclusion, electrocoagulation is a promising, efficient, and economical method for treating domestic wastewater. It offers several advantages over conventional chemical coagulation, including lower sludge production and the absence of added salts in the treated water, resulting in higher water quality and reduced environmental impact.

Declaration of Competing Interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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Author Contributions

Author Ali J. Jaeel proposed the research problem. In addition, author Roua S. Sahip collected recent articles and organized them into simple shapes. Authors Ali J. Jaeel and Roua S. Sahip discussed the proposed design, the results, and the final version of this paper.

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