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Electrocoagulation Applied to Domestic Wastewater Treatment: Statistical Optimization and Validation in Different Real Matrices

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Abstract

The increasing demand for sustainable water management has prompted the search for efficient domestic wastewater treatment technologies. Electrocoagulation (EC) has emerged as a promising alternative owing to its simplicity, efficiency, and potential for decentralized applications. This study investigated EC for treating domestic wastewater, focusing on optimizing operational parameters via the design of experiments (DoE). Initially, raw wastewater was characterized, followed by a fractional factorial design to screen for significant variables: operating time, current density, initial pH, and NaCl dosage. Results revealed that current density and pH were the most influential parameters on Chemical Oxygen Demand (COD) removal. Subsequently, a Central Composite Rotational Design (CCRD) optimized these key parameters. Optimal conditions were a current density of 85 A/m² and pH of 5.5, achieving COD removal efficiencies up to 78.2%. A cost analysis indicated the economic feasibility of EC for smaller effluent volumes, with an estimated operational cost of US$1.23 per cubic meter treated. Applying this methodology to real sewage matrices (Federal University of Sergipe WWTP and a residential condominium) showed variations in Biochemical Oxygen Demand (BOD), COD, and turbidity removal. These findings confirm EC's potential as a sustainable solution for domestic wastewater treatment in isolated communities.

Keywords: wastewater treatment; electrocoagulation; experimental design; organic matter removal; sustainability

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1. Introduction

Adequate management of water resources is fundamental to a sustainable future, and efficient treatment of domestic wastewater plays a pivotal role. Through Sustainable Development Goal 6 (SDG 6), the United Nations (UN) has established a target to ensure universal access to sanitation by 2030, emphasizing sustainable management, water quality improvement, and wastewater treatment. In Brazil, the state of basic sanitation remains a challenge, with a significant portion of the population lacking access to wastewater collection and treatment systems [1]. This situation is exacerbated in rural and remote communities, where the absence of centralized treatment networks is prevalent.

Against this backdrop, the pursuit of decentralized, low-cost, and easily maintainable wastewater treatment technologies is imperative. Electrocoagulation (EC), an electrochemical process, has garnered increasing attention as a promising alternative for wastewater treatment, particularly when integrated with renewable energy sources [2–7], including domestic wastewater [8]. EC relies on the electrolytic dissolution of metallic electrodes—typically aluminum or iron—to generate coagulants in situ. These coagulants destabilize and aggregate organic and inorganic pollutants within the effluent, facilitating their removal via sedimentation or flotation [9]. Its

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advantages include operational simplicity, reduced sludge production compared to conventional chemical coagulation, and the feasibility of using inexpensive electrode materials.

The process efficiency is highly dependent on the specific effluent characteristics and chosen operational conditions, underscoring the necessity of optimization studies for each application. Optimizing operational parameters, such as the initial pH, current density, and electrode material, is crucial for maximizing process efficiency [10,11] while minimizing operational costs.

Recent studies have corroborated the efficacy of EC in various configurations and matrices. [12] demonstrated Chemical Oxygen Demand (COD) removal rates exceeding 75% in domestic wastewater using aluminum electrodes, showing potential for non-potable reuse. [3] employed Response Surface Methodology (RSM) to optimize EC for cefazolin removal, achieving an 85.65% efficiency under ideal operating conditions. [13] assessed an electrocoagulation-flotation system, attaining removal efficiencies of up to 78.9% for COD and 90.1% for turbidity, although final pH correction was required to comply with environmental regulations. Furthermore, a systematic review by [14] highlighted that EC can achieve removal efficiencies greater than 90% for both COD and turbidity, particularly with aluminum or combined Al/Fe electrodes. The review also identified pH, current density, and reactor design as the determinant variables for process performance. Moreover, the literature has explored the use of non-conventional electrodes and the coupling of EC with other techniques, such as advanced oxidation processes and electroflotation, to enhance efficiency and mitigate the generation of byproducts [15]. [16] conducted a systematic review and concluded that, beyond removing organic matter and turbidity, EC has been successfully applied to eliminate emerging pollutants, including microplastics and per- and polyfluoroalkyl substances (PFAS).

Design of Experiments (DoE), particularly fractional factorial design and Central Composite Rotational Design (CCRD), coupled with Response Surface Methodology (RSM), are powerful statistical tools for process optimization and identification of optimal operational conditions [17,18]. A factorial design facilitates the simultaneous evaluation of multiple factors and their potential interactions. The CCRD is particularly effective for optimizing processes with nonlinear responses, as it allows the development of quadratic models and visualization of response surfaces. RSM assists in identifying the optimal operating conditions and elucidating the relationship between independent and response variables.

The growing demand for decentralized domestic wastewater treatment solutions, especially for rural and remote communities, reveals a significant gap in the current state-of-the-art sanitation technologies. Despite recent advances, many existing approaches lack operational simplicity, economic viability, and adaptability to diverse matrices. In this context, the present study proposes the application of EC as an innovative solution that combines low cost, ease of maintenance, and potential for integration with renewable energy sources. Beyond its technical merits, this technology offers the potential for direct social impact by promoting access to basic sanitation in underserved areas, thereby aligning with the Sustainable Development Goals (SDG 6).

This study aimed to evaluate the efficiency of the EC process for treating domestic wastewater, focusing on optimizing operational parameters through an experimental design approach. This study focused on identifying the optimal conditions for current density and initial pH to maximize organic matter removal using CCRD and RSM. Furthermore, the applicability of the optimized methodology was assessed using different real wastewater matrices to verify the robustness and flexibility of the process. A detailed analysis of the results and conclusions of this study will contribute to the advancement of knowledge in domestic wastewater treatment and the development of more efficient and sustainable solutions for basic sanitation.

2. Materials and Methods

2.1. Study Site and Sample Collection

This study was based on raw domestic wastewater sourced from a community in Estância, Sergipe, Brazil. Primary samples were collected from a partially decommissioned wastewater treatment plant (WWTP) operated by the local Municipal Water and Sewage Service (SAAE). To assess the robustness of the electrocoagulation process under different real-world conditions, supplementary wastewater samples were obtained from the WWTP at the Federal University of Sergipe (UFS) and from a separate urban residential condominium.

2.2. Wastewater Characterization

The collected wastewater samples were comprehensively characterized physicochemically and microbiologically. The analyzed parameters included Total Organic Carbon (TOC), Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), pH, Settleable Solids, Oil and Grease, and Total Coliforms. All analytical procedures were conducted in strict accordance with the protocols outlined in the Standard Methods for the Examination of Water and Wastewater [19]. This initial characterization was essential for identifying the target pollutants and guiding the subsequent experimental design.

2.3. Electrocoagulation Reactor Setup

Electrocoagulation experiments were performed in a bench-scale prismatic reactor constructed from polymethyl methacrylate (PMMA) with a working volume of 3.0 L. The system was operated at ambient temperature (24 ± 1 °C) and maintained under constant agitation at 300 rpm. The electrode assembly consisted of four aluminum plates (each with a surface area of 225 cm^2) arranged in a monopolar parallel configuration with an interelectrode gap of 1.0 cm. Aluminum was selected as the electrode material because of its proven high efficiency, broad applicability, and low cost [15]. The reactor design and electrode geometry were based on established recommendations to maximize mass transfer and minimize the hydraulic dead zones [11].

2.4. Experimental Design and Statistical Optimization

An initial screening of potentially influential variables was performed using a 2^{4-1} fractional factorial design. The factors investigated were the operating time, current density, initial pH, and NaCl addition. The variables with the highest statistical significance were selected for process optimization. This subsequent stage was carried out using a five-level Central Composite Rotational Design (CCRD).

Response Surface Methodology (RSM) was employed to model the behavior of the system. This allowed the development of a quadratic equation to predict the process response and identify the optimal operating conditions. This statistical approach is widely recommended for systems involving nonlinear interactions and multiple variables, as it significantly reduces the number of experimental runs required while enhancing the statistical robustness [17,20].

2.5. Performance Evaluation and Cost Analysis

The primary response variable for process optimization was the COD removal efficiency, which was calculated from the concentrations before and after treatment. Confirmatory experiments were conducted under the optimal conditions predicted by the CCRD model to validate its accuracy and reliability. The specific energy consumption was determined by monitoring the voltage and current during the operating time. Electrode consumption was quantified gravimetrically by measuring the mass loss of the anodes after each experiment was performed.

An operational cost analysis, expressed in US dollars per cubic meter of treated wastewater (US\$/m^3), was estimated based on the average consumption of energy and electrode materials. This calculation used local utility rates for electricity (US\$ 0.15/kWh) and the market price for aluminum (US\$ 0.002/g). Although this analysis does not encompass capital investment or maintenance costs, it provides a practical estimate of the system's economic feasibility, following the methodology reported by [21].

3. Results

A thorough characterization of the effluent is essential to identify its contaminants and quantify their concentrations. This initial analysis provided the necessary baseline to develop and refine the experimental parameters for the EC process, ensuring that the treatment conditions could be optimized for the maximum removal efficiency of the identified pollutants.

3.1. Characterization of Raw Domestic Wastewater

The initial characterization of domestic wastewater from the Estância municipality (Table 1) was consistent with the typical composition of raw domestic wastewater reported in the literature.

Table 1. Characterization of the raw effluent collected for the study.

Analyzed Parameter	Result
Total Organic Carbon	130.0 mg/L
Chemical Oxygen Demand (COD)	688.33 mg/L
Total Coliforms	>1.6E^{+7}
Settleable Solids	8.0 mg/L
Oil and Grease	20.0 mg/L
Biochemical Oxygen Demand (BOD)	220 mgO$_2$/L
pH	6.37

3.2. Factor Screening

A 2^{4-1} fractional factorial design with a center point was employed to identify the variables with the most significant influence on the electrocoagulation process. This approach was chosen for its efficiency in reducing the number of experimental runs while still allowing the analysis of the main effects [17,20]. This initial exploratory design simultaneously evaluated the effects of four operational factors: operating time, current density, initial pH, and NaCl concentration. Each factor was tested at three levels, corresponding to the coded values of -1, 0, and +1, which are the standards for statistical studies with continuous variables. The response variable was the COD removal efficiency (%).

Table 2 presents a detailed summary of how each experimental run influenced the reduction in COD.

Table 2. Experimental matrix and results for the fractional factorial design.

Time (minutes)	Current density (A/m^2)	pH	NaCl addition (g/L)	COD reduction (%)
30	60	6	0	31.66
60	80	6	0	50.32
60	60	6	0.5	28.23
30	80	6	0.5	57.73
60	60	8	0	34.82
30	80	8	0	15.56
30	60	8	0.5	15.53
60	80	8	0.5	24.62
45	70	7	0.25	37.30
45	70	7	0.25	20.45
45	70	7	0.25	50.75

The results were statistically analyzed using Statistica software, and a Pareto chart was generated to visualize the individual and interactive effects of each variable (Figure 1).

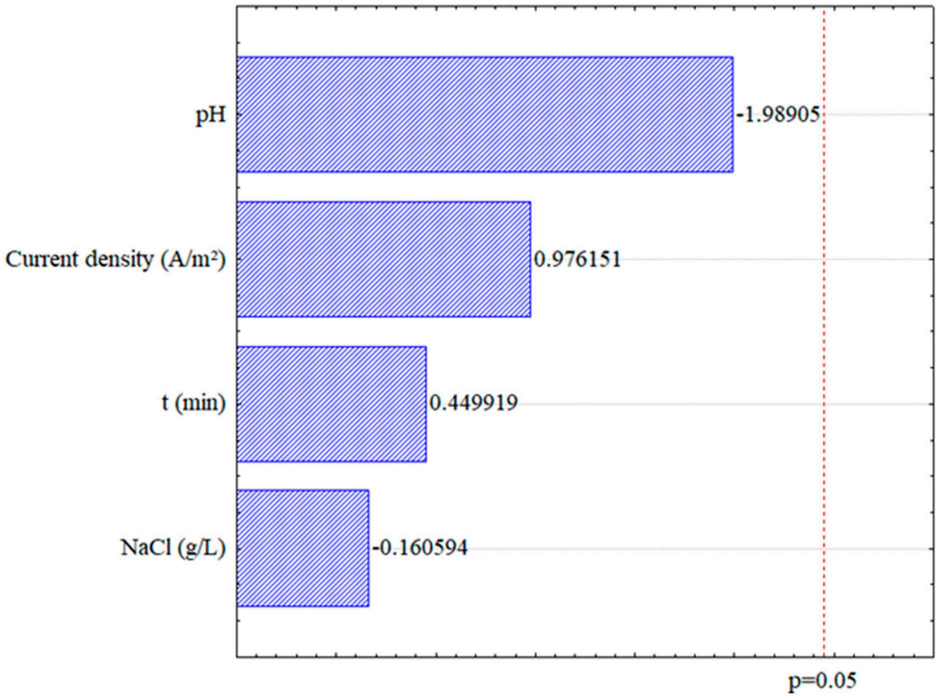

Figure 1. Pareto chart of the standardized effects on COD removal.

3.3. Process Optimization

Based on the factor screening results, a CCRD was implemented to optimize the two most influential parameters, current density and pH, across five levels (Table 3), while all other conditions were held constant. The CCRD was selected for its ability to fit quadratic models and identify optimal operating regions, a methodology widely employed for complex electrocoagulation processes with interacting variables [27,28].

Table 3. Coded and real values for the CCRD factors.

Parameter	Level (-α)	Level (-1)	Level (0)	Level (+1)	Level (+α)
Current density (A/m²)	67.3	70	75	80	82.07
pH	5.79	6	6.5	7	7.21

The CCRD comprised 12 experimental runs, which included factorial, axial ($\alpha = \pm 1.414$), and center points. Table 4 presents the CCRD experimental matrix and corresponding results. Response surfaces were generated to visualize the influence of the independent variables and identify the optimal operating region (Figures 2 and 3).

Table 4. CCRD matrix and experimental results for COD removal.

Experiment	Current density (A/m²)	pH	COD Reduction (%)
1	70	6	20
2	70	7	25.64
3	80	6	34.20
4	80	7	32.50
5	67.93	6.5	27.26
6	82.07	6.5	72.82
7	75	5.79	61.61
8	75	7.21	32.38
9	75	6.5	24.62
10	75	6.5	30.49
11	75	6.5	33.32

12	75	6.5	34.36

Figure 2 displays the response surface as a 2D contour plot, whereas Figure 3 illustrates the 3D response surface of the removal efficiency as a function of the two variables.

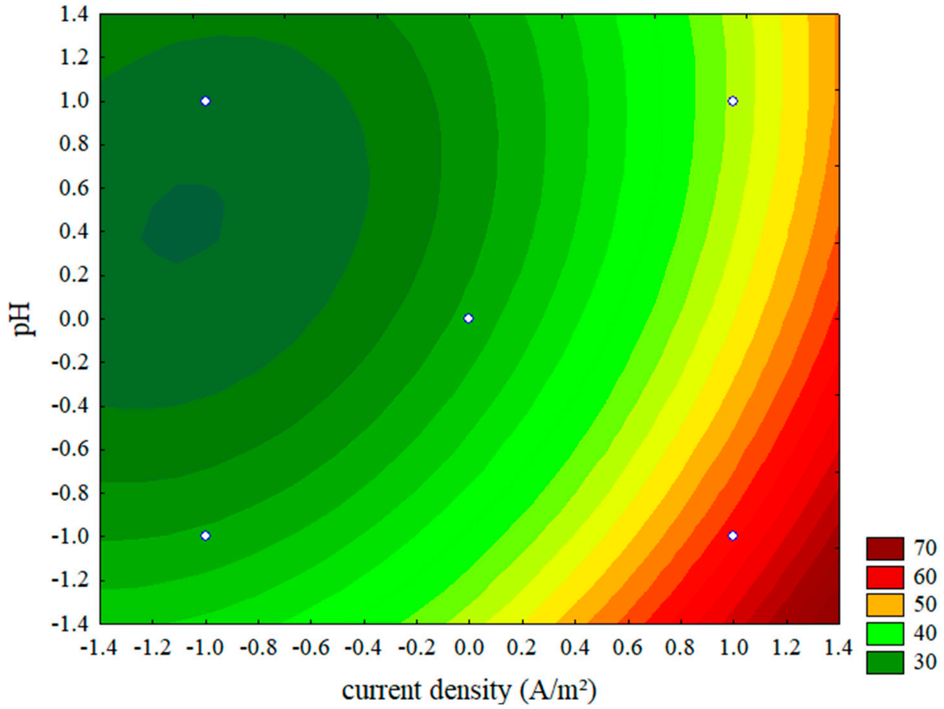

Figure 2. Response surface methodology (RSM) contour plot (2D) for COD removal.

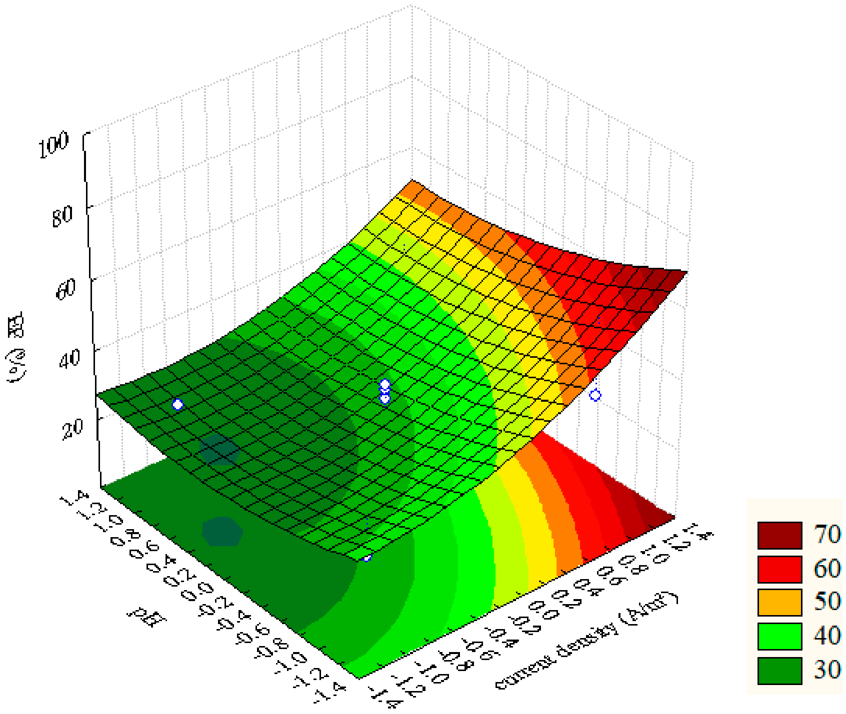

Figure 3. 3D response surface for COD removal, including axial points.

3.4. Validation of the Optimized Model and Cost Analysis

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To validate the optimal conditions predicted by the CCRD model (current density of 85 A/m² and pH of 5.5), confirmatory replicate experiments were conducted. The results are shown in Table 5.

Table 5. Confirmatory experimental runs at the optimal setpoint and corresponding COD reduction.

Experiment	Current density (A/m²)	pH	COD Reduction (%)
1	85	5.5	45.06
2	85	5.5	78.20
3	85	5.5	57.63

A cost analysis of the EC process, which is essential for determining its practical applicability, was performed by measuring the energy consumption (from current and voltage readings) and electrode mass consumed during the experiments (Table 6).

Table 6. Operational parameters for energy and electrode consumption analysis.

Experiment	Power (W)	Time (Hours)	Energy consumption (kWh)	Electrode consumption (g/h)
1	14.52	0.5	0.007258	0.1954
2	16.04	0.5	0.008022	0.1919
3	14.33	0.5	0.007162	0.1563
Average	14.96	0.5	0.007481	0.1812

Table 7 provides a comparative summary of these results with those of other studies in the literature.

Table 7. Comparative analysis of electrocoagulation studies for wastewater treatment.

Effluent Type	Operating Conditions	COD Removal (%)	Energy consumption (kWh)	Cost (US$/m³)	Reference
Domestic sewage	85 A/m², pH 5.5, 60 min	78.2	0.0075	1.23	This study
Domestic sewage	EC-Flotation, 1.5 A, 20 min (no pH adjustment)	79.8	-	-	[12]
Industrial wastewater	Al, 20 mA/cm², pH 6, 30 min	75–85	0.15–0.25	-	[31]
Domestic sewage	EC- Flotation, 2.5 A, pH 6, 25 min	82.9	0.021	-	[13]
Industrial textile wastewater	20 mA/cm², pH 6, 30 min	-	0.45	0.21	[21]

3.5. Application to Different Sewage Matrices

To assess the robustness and adaptability of the optimized methodology, the EC process was applied to two different sewage matrices: one from the Federal University of Sergipe's WWTP (WWTP-UFS) and another from an urban residential condominium (URC) (Figure 4). This stage was designed to investigate the impact of effluent composition on process efficiency and to test the resilience of the statistical model under distinct real-world conditions.

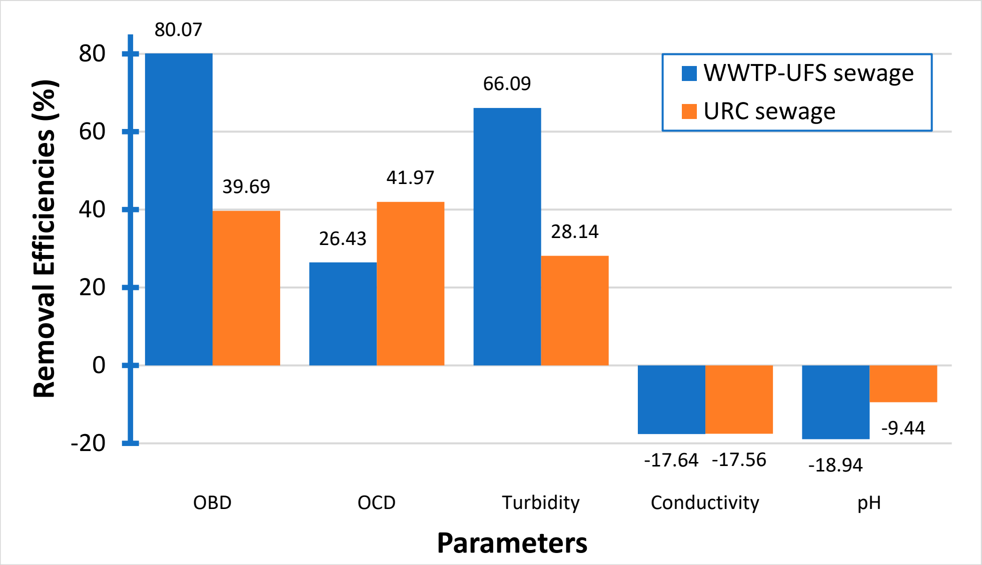

Figure 4. Comparison of removal efficiencies for WWTP-UFS and URC sewage.

4. Discussion

4.1. Characterization of Raw Domestic Wastewater

The raw domestic wastewater exhibited high concentrations of COD (688.33 mg/L) and BOD (220 mg/L). These values significantly exceed the discharge limits for water bodies stipulated by Brazilian environmental regulations [22], which set maximums of 120 mg/L for COD and 60 mg/L for BOD for direct discharge into Class 2 receiving waters. These data underscore the necessity of effective treatment prior to disposal, particularly in regions where the receiving water body has a low dilution capacity.

Comparatively, international guidelines such as the [23] and those of the [24] impose stringent standards for treated effluents, with typical secondary treatment limits of 125 mg/L for COD and 30 mg/L for BOD. This comparison highlights that the wastewater analyzed in this study possessed an organic load substantially higher than the permissible discharge standards, thereby justifying the selection of electrocoagulation as a viable treatment alternative. Furthermore, the elevated concentration of total coliforms ($>1.6\times10^7$ MPN/100 mL) indicates a significant health risk. This reinforces the importance of technologies that not only remove organic matter but also provide complementary disinfection, as recommended by [25] for individual treatment systems.

4.2. Factor Screening

At a 95% confidence level ($p = 0.05$), none of the variables or their interactions were statistically significant. However, the Pareto chart clearly indicated that the initial pH and current density were the most influential factors, despite not reaching the threshold for statistical significance ($p < 0.05$). This lack of statistical significance may be attributed to inherent experimental variability and a limited number of replicates, suggesting that future studies could benefit from more replicates or alternative designs with greater statistical power.

These findings align with those of previous electrocoagulation studies, such as the review by [14], which also identified pH and current density as critical parameters for organic matter removal. The minor influence of NaCl has been similarly reported by [26], who attributed it to the sufficient conductivity provided by metallic ions released from the electrodes. Therefore, given the clear predominance of current density and initial pH, a Central Composite Rotational Design (CCRD) was conducted to model the system's behavior more precisely and determine the optimal operating conditions. As the Pareto chart suggested that higher efficiency could be achieved by increasing the current density and decreasing the pH, the CCRD was ideal for expanding the experimental region through the inclusion of axial points. The results of the optimization stage are presented in Section 4.3.

4.3. Process Optimization

The Table 4 data revealed a pattern consistent with expectations and the literature. A marked increase in the treatment efficiency was observed in the runs conducted at the axial points (Experiments 6 and 7). Consequently, it became necessary to compare the comprehensive model with an analysis of the factorial subset (experiments 1-4 and the center point).

The response surfaces indicated that maximizing the current density was crucial for enhancing the COD removal efficiency. Although the influence of pH was less pronounced, a lower pH also contributed to process optimization, particularly when combined with a higher current density, as evidenced by the curvature of the response surface (Figure 2).

The statistical modeling results of this study are well supported by the specialized literature. The sequential application of a fractional factorial design and CCRD successfully identified current density and initial pH as the most influential variables for COD removal, which aligns with the findings of [12] and [18]. While those authors employed more direct experimental approaches, the present study incorporated Response Surface Methodology (RSM), yielding a predictive model with superior accuracy and broader applicability.

The statistical analysis presented herein also corroborates the results of [28], who utilized a central composite design and RSM to optimize electrocoagulation for the simultaneous removal of micropollutants. Consistent with our findings, they identified significant nonlinear relationships and quadratic effects among operational parameters, particularly between pH and current density. These parallels reinforce the suitability of RSM as a robust tool for exploring the combined effects of operational factors in the EC process, thereby validating the adopted modeling.

4.4. Validation of the Optimized Model and Cost Analysis

The Table 5 results confirm that optimizing the current density and pH can produce significant variations in pollutant removal, as demonstrated by the replicate runs, which is consistent with the findings of [29]. The observed variance in COD removal percentages among replicates can likely be attributed to uncontrolled or unmodeled operational factors inherent to the EC system, a phenomenon extensively discussed by [30].

Based on a local electricity tariff of US$0.15/kWh and a market price for aluminum of US$0.002/g, the operational costs were estimated to be US$0.00369 per hour, and US$1.23 per cubic meter of treated effluent. For comparison, [21] reported a cost of US$0.21/m^3 for treating a synthetic dye-containing effluent, albeit with higher energy consumption (0.45 kWh/m^3). Despite the cost difference, our results affirm the technical and economic viability of EC for real wastewater, particularly considering the process's adaptability and low environmental impact.

Although this operational cost is subject to variation based on scale and local conditions, it is competitive with other decentralized treatment technologies, especially for smaller effluent volumes. The simplicity of the EC system and its low initial capital cost are additional advantages. However, a comprehensive feasibility analysis requires a more detailed economic evaluation, including the long-term capital and maintenance costs of a full-scale system.

As can be seen in Table 7 this study offers significant advantages over previous studies, primarily through the application of EC to real domestic wastewater from two distinct matrices, which lends greater robustness and practical relevance to the findings. Moreover, when coupling technical performance with economic viability, the average operational cost of US$ 1.23/m ^{3} in this study is associated with a very low estimated energy consumption of just 0.0075 kWh/m^3, establishing it as an efficient alternative for decentralized applications. Similar outcomes were reported by [13], who used an EC-flotation system for domestic wastewater treatment intended for urban reuse. Under their optimized conditions, they achieved 82.9% COD and 95.8% turbidity removal, with an energy consumption of approximately 0.021 kWh/m³. The COD removal efficiency achieved in this study (up to 78.2%) falls within the range reported by [31] for optimized EC systems, reinforcing the robustness of the process. This energy consumption is notably lower than the values from other studies, such as [21], who reported 0.45 kWh/m³ under controlled, synthetic conditions (Table 7). This underscores the attractiveness of EC in contexts where energy is limited or grid access is unavailable to consumers.

The present work is also distinguished from the studies of [13] and [12] by testing the EC process on multiple real domestic wastewater matrices, thereby proving its versatility and operational robustness. The use of CCRD with RSM further enhances statistical rigor and reliability, yielding a model that is replicable in diverse settings.

However, this study has certain limitations. The relatively long operating time (60 min), although effective, could constrain the application of this technology in continuous systems with higher flow rates. Furthermore, the focus on classical parameters (COD and BOD) restricts the analysis of emerging pollutants. In this regard, studies by [28] and [16] suggest that broadening the analytical scope to include contaminants such as pharmaceuticals, PFAS, and microplastics and integrating EC with complementary techniques would further enhance the environmental impact of this technology.

4.5. Application to Different Sewage Matrices

Figure 4 presents a comparative analysis of BOD, COD, and turbidity removal, as well as the changes in conductivity and pH. BOD removal was more efficient for the WWTP-UFS sewage (80.07%), whereas COD removal was superior for URC sewage (66.09%). This discrepancy may be linked to the proportion of biodegradable organic matter in each matrix type. The WWTP sewage, being more diluted and homogeneous, might favor the removal of easily oxidizable compounds, whereas the URC sewage could contain a higher load of refractory compounds, thereby affecting the COD removal efficiency.

Turbidity removal was significant in both matrices, reinforcing the EC's capacity to improve the physical characteristics of the effluent. Conversely, the electrical conductivity increased post-treatment, which was an expected outcome owing to the release of aluminum ions (Al^{3+}) during electrode dissolution. This behavior was also reported by [32], who observed increased pH and conductivity in EC-treated effluents intended for reuse in forestry.

The increase in the final pH of both matrices was attributed to the generation of hydroxide ions (OH^-) at the cathode. This can be advantageous for subsequent disinfection steps but requires careful management if the treated effluent is intended for direct reuse.

These results demonstrate that although the optimized methodology is effective across different contexts, the raw effluent composition directly influences the process efficiency. Therefore, for each new matrix, fine-tuning of the operational parameters, such as the reaction time, current density, and electrode geometry, is recommended to maximize the performance. The application of EC to diverse real-world matrices confirms its versatility but also highlights the importance of contextualized calibration, particularly when aiming for standardized efficiency in decentralized systems.

5. Conclusions

This study demonstrates that electrocoagulation (EC) is an efficient, economical, and technically feasible alternative for domestic wastewater treatment, particularly for decentralized applications and in operationally constrained environments. The successful application of an optimization methodology, based on a Central Composite Rotational Design (CCRD) and Response Surface Methodology (RSM), identified the ideal operating conditions as a current density of 85 A/m² and an initial pH of 5.5. Under these conditions, the process achieved COD and BOD removal efficiencies of up to 78.2% and exceeding 80%, respectively.

Validation of the process across different wastewater matrices sourced from a university wastewater treatment plant and a residential condominium underscored the robustness and adaptability of EC technology, even when challenged by variations in effluent composition. The cost analysis confirmed the economic viability of the process for moderate wastewater volumes, with an estimated operational cost of US$1.23/m³. This was achieved with remarkably low energy consumption of 0.0075 kWh/m³, representing highly competitive energy performance compared to conventional treatment alternatives.

Furthermore, these findings are in alignment with the results of studies such as [13], who reported 82.9% COD and 95.8% turbidity removal using an EC–Flotation system for urban reuse. This congruence indicates that EC, whether as a standalone process or integrated with other technologies, has significant potential for advanced effluent treatment.

In conclusion, based on its strong technical performance, simplicity of construction, and affordability, EC emerges as a strategic technology to help achieve Sustainable Development Goal 6 (SDG 6: Clean Water and Sanitation), particularly in regions with limited infrastructure. Future research should focus on integrating EC with other advanced techniques (e.g., photocatalysis or ozonation) and incorporating renewable energy sources and automated control systems to further amplify its positive environmental and social impacts.

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Abbreviations

The following abbreviations are used in this manuscript:

EC	Electrocoagulation
DoE	Design of experiments
CCRD	Central Composite Rotational Design
RSM	Response Surface Methodology
PFAS	Polyfluoroalkyl substances
WWTP	Wastewater treatment plant
UFS	Federal University of Sergipe
URC	Urban residential condominium

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