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Simulation-Based Analysis and Adaptive Optimization of Electrocoagulation for Wastewater Treatment from Wood-Based Industries

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Abstract

Wastewater generated from wood-based industries contains a complex mixture of suspended solids, organic matter, and recalcitrant pollutants that are difficult to remove using conventional treatment techniques. Electrocoagulation has emerged as an effective alternative due to its ability to generate coagulants in situ and promote pollutant destabilisation through electrochemical reactions. However, practical deployment of electrocoagulation systems is often limited by high energy consumption and the lack of systematic operating strategies. This work presents a comprehensive simulation-based investigation of electrocoagulation for industrial wastewater treatment, with a particular focus on pollutant removal efficiency, energy consumption, and spatial treatment uniformity. A physics-based mathematical

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model is developed to describe electric potential distribution, current density, metal ion generation, pollutant transport, and reaction kinetics within a two-dimensional reactor domain. The governing equations are solved numerically using a finite-difference framework, enabling detailed parametric analysis under varying voltage, conductivity, and reaction-rate conditions. Based on the insights obtained from static operation, an adaptive electrocoagulation framework is proposed in which the applied voltage is dynamically regulated in response to system state indicators. Simulation results demonstrate that the adaptive strategy achieves a high final pollutant removal of 96.37% while consuming only 9.84 kJ of electrical energy, with stable voltage behaviour and limited fluctuations. Comparative analysis shows that this adaptive approach provides a superior removal–energy trade-off compared to static high-voltage operation and outperforms several recently reported electrocoagulation studies. The outcomes of this research establish the effectiveness of adaptive, physics-informed control for electrocoagulation systems and provide a scalable framework for energy-efficient wastewater treatment in wood-based and similar industrial sectors.

Keywords: Electrocoagulation; Wastewater treatment; Adaptive control; Energy optimization; Numerical simulation; Wood-based industries

1 Introduction

Industrial wastewater generated from wood-based and allied processing industries poses a persistent challenge due to the presence of high organic load, suspended solids, colour-causing compounds, and recalcitrant pollutants. Conventional treatment methods, including sedimentation, biological treatment, and chemical coagulation, often show limited effectiveness when dealing with complex industrial effluents characterised by variable composition and high pollutant

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strength [1, 2]. As environmental discharge regulations become increasingly stringent, there is a growing need for treatment technologies that can achieve high pollutant removal while maintaining acceptable energy consumption and operational sustainability.

Advanced oxidation processes (AOPs) and electrochemical treatment techniques have gained attention as promising alternatives or complements to conventional wastewater treatment systems [3, 4]. Among these, electrocoagulation (EC) has emerged as a robust and flexible technology capable of treating a wide range of industrial wastewaters, including effluents from wood processing, pulp and paper, textile, and food industries [5, 6]. In EC, sacrificial metal electrodes dissolve under an applied electric field, generating metal hydroxide species in situ that destabilise and remove pollutants through charge neutralisation, adsorption, and sweep flocculation mechanisms.

Compared to conventional chemical coagulation, electrocoagulation offers several advantages, such as reduced chemical handling, lower sludge toxicity, and improved removal of finely dispersed contaminants [7]. However, despite these advantages, large-scale adoption of EC remains constrained by challenges related to energy consumption, electrode passivation, and process optimisation [8]. In particular, the trade-off between pollutant removal efficiency and electrical energy input remains a critical issue that directly affects the economic feasibility of EC-based treatment systems.

1.1 Motivation for Physics-Based Modelling and Numerical Analysis

Most existing EC studies rely heavily on experimental investigations conducted under fixed operating conditions, where voltage, current density, and electrolyte conductivity are kept constant throughout the treatment duration [9, 10]. While such studies provide valuable empirical insights, they often lack a rigorous physics-based framework capable of explaining spatial and temporal variations in pollutant concentration, electric field distribution, and coagulant

Received: August 20, 2025

generation within the reactor. As a result, optimisation is typically performed through trial-and-error experimentation, which is time-consuming and system-specific.

Physics-based mathematical modelling offers a systematic approach to understanding EC processes by explicitly coupling electric potential distribution, Faradaic electrode reactions, and pollutant transport mechanisms [11, 12]. Reaction–diffusion formulations, combined with electrostatic field models, enable the prediction of pollutant decay, coagulant formation, and spatial non-uniformities that are difficult to measure experimentally. Such models are particularly valuable for identifying inefficient operating regimes where excessive energy is consumed without commensurate improvement in removal efficiency.

Recent numerical studies have demonstrated that static EC operation can lead to strong spatial gradients near electrode surfaces, resulting in localised over-treatment and unnecessary energy expenditure [13, 14]. These findings highlight the need for advanced control strategies that can dynamically adapt operating conditions based on the evolving state of the treatment process. However, most modelling efforts reported in the literature remain limited to static voltage or current operation, without incorporating adaptive or closed-loop control mechanisms.

1.2 Adaptive Operation and Energy–Removal Trade-Off Analysis

From a practical perspective, the ultimate goal of EC system design is not merely to maximise pollutant removal, but to achieve a balanced compromise between treatment performance, energy consumption, and process stability. Several authors have reported that increasing applied voltage or current density improves removal efficiency but leads to disproportionately higher energy consumption and accelerated electrode degradation [15, 16]. This non-linear relationship underscores the importance of operating EC systems near an optimal point rather than at maximum power input.

Received: August 20, 2025

Adaptive control strategies, widely employed in chemical process engineering, offer a potential solution to this challenge by adjusting control variables in response to real-time system behaviour [17]. In the context of electrocoagulation, adaptive voltage or current control can, in principle, enhance removal during critical treatment phases while reducing energy input once diminishing returns set in. Despite its promise, adaptive EC operation has received limited attention in the open literature, particularly in combination with spatially resolved numerical models.

Recent experimental studies published in 2024–2025 have reported high pollutant removal under optimised static EC conditions, but often at the cost of substantial energy input when reported on a per-volume basis [18, 19]. Moreover, differences in reactor geometry, pollutant type, and reporting units complicate direct comparison across studies, reinforcing the need for controlled numerical frameworks where parameters can be varied systematically.

1.3 Contribution and Scope of the Present Study

In this work, a comprehensive numerical framework is developed to analyse and optimise electrocoagulation-based wastewater treatment for wood-based industrial effluents. The study integrates physics-based system modelling, static parametric analysis, and adaptive control within a unified simulation environment. First, a two-dimensional electrocoagulation reactor model is formulated by coupling electric potential distribution, Faradaic coagulant generation, and pollutant reaction–diffusion dynamics. This model is used to systematically evaluate the influence of applied voltage, electrolyte conductivity, and reaction kinetics under static operating conditions.

Second, performance metrics including pollutant removal efficiency, spatial uniformity of treatment, and cumulative energy consumption are defined and computed to characterise the inherent trade-offs of static EC operation. Finally, an adaptive voltage con-

Received: August 20, 2025

trol framework is introduced, in which operating voltage is dynamically adjusted based on evolving removal behaviour and energy efficiency considerations. The proposed approach enables improved removal–energy balance while maintaining stable system operation.

By combining numerical modelling with adaptive process logic, this study provides quantitative insight into how electrocoagulation performance can be enhanced beyond conventional static operation. The results contribute to a deeper understanding of EC dynamics and offer a practical pathway towards more energy-efficient and controllable electrochemical wastewater treatment systems.

2 Materials and Methods

This section describes the materials considered, the system configuration, and the numerical methodology adopted to investigate electrocoagulation-based wastewater treatment. The modelling framework integrates electrochemical transport, reaction kinetics, and energy accounting under both static and adaptive operating conditions. The methods are designed to ensure physical consistency, numerical stability, and reproducibility of results.

2.1 Wastewater Characteristics and Assumptions

The present study considers wastewater representative of wood-based industrial effluents, which typically contain suspended solids, dissolved organic matter, and recalcitrant pollutants contributing to elevated chemical oxygen demand (COD). Rather than focusing on a specific chemical species, a generic pollutant concentration field $C(\mathbf{x}, t)$ is modelled, enabling generalisation across different contaminant classes, as adopted in prior electrocoagulation modelling studies [5, 8].

The initial pollutant concentration is assumed spatially uniform and normalised as

$$C(\mathbf{x}, 0) = C_0 = 1, \tag{1}$$

Received: August 20, 2025

which allows direct comparison of relative removal efficiency across operating conditions. The electrolyte is treated as electrically conductive, incompressible, and isothermal, with constant conductivity σ.

2.2 Electrocoagulation Reactor Configuration

A two-dimensional rectangular electrocoagulation domain is considered, representing a batch EC reactor with parallel plate electrodes. One electrode acts as the anode and the other as the cathode, separated by an inter-electrode distance d. Iron electrodes are assumed, consistent with common industrial practice [6].

The applied potential difference across the electrodes is denoted by $V(t)$, which may be constant (static operation) or time-varying (adaptive operation). The electric potential field $\phi(\mathbf{x}, t)$ within the electrolyte satisfies the charge conservation equation

$$\nabla \cdot (\sigma \nabla \phi) = 0, \tag{2}$$

subject to Dirichlet boundary conditions at the electrode surfaces,

$$\phi = 0 \quad \text{at cathode}, \qquad \phi = V(t) \quad \text{at anode}. \tag{3}$$

2.3 Electric Field and Current Density

The local electric field $\mathbf{E}$ is obtained from the electric potential as

$$\mathbf{E} = -\nabla \phi, \tag{4}$$

and the current density $\mathbf{J}$ follows Ohm's law,

$$\mathbf{J} = \sigma \mathbf{E}. \tag{5}$$

The spatially averaged current density $\bar{J}$ is used to estimate electrochemical reaction rates and energy consumption, consistent with Faradaic theory [7].

Received: August 20, 2025

2.4 Coagulant Generation Model

At the anode, iron dissolves according to the anodic reaction

$$\mathrm{Fe} \rightarrow \mathrm{Fe}^{2+} + 2e^{-}. \tag{6}$$

The rate of ferrous ion generation is governed by Faraday's law,

$$R_{\mathrm{Fe}^{2+}} = \frac{\eta_F |\mathbf{J}|}{nF}, \tag{7}$$

where η_F is the Faradaic efficiency, $n = 2$ is the number of electrons transferred, and F is Faraday's constant. The generated metal ions rapidly hydrolyse to form metal hydroxide flocs, which act as coagulants.

2.5 Pollutant Transport and Reaction Kinetics

Pollutant removal is modelled using a reaction–diffusion equation,

$$\frac{\partial C}{\partial t} = D\nabla^2 C - kC, \tag{8}$$

where D is the effective diffusion coefficient and k is the apparent first-order reaction rate constant representing coagulation, adsorption, and aggregation processes [11].

The reaction term kC captures the net removal effect of electrochemically generated coagulants. This abstraction is widely used in EC simulations where explicit floc dynamics are not resolved [13].

2.6 Boundary and Initial Conditions

No-flux boundary conditions are applied at the reactor walls,

$$\mathbf{n} \cdot \nabla C = 0, \tag{9}$$

ensuring mass conservation within the domain. The initial condition for pollutant concentration is given by Eq. (1).

2.7 Performance Metrics

The pollutant removal efficiency η is defined as

$$\eta = 1 - \frac{\bar{C}(t_f)}{C_0}, \tag{10}$$

where $\bar{C}(t_f)$ is the spatially averaged concentration at the final simulation time t_f.

Spatial treatment uniformity is quantified using a uniformity index,

$$U = 1 - \frac{\mathrm{std}(C)}{\mathrm{mean}(C)}, \tag{11}$$

where $\mathrm{std}(C)$ and $\mathrm{mean}(C)$ are computed over the final concentration field. Higher values of U indicate more homogeneous treatment.

2.8 Energy Consumption Model

The instantaneous electrical power input is given by

$$P(t) = V(t)I(t), \tag{12}$$

where $I(t)$ is the total current obtained by integrating the current density over the electrode area. The cumulative energy consumption is calculated as

$$E = \int_0^{t_f} P(t)\, dt. \tag{13}$$

This formulation enables direct comparison of different operating strategies in terms of energy efficiency, as recommended in electrochemical treatment studies [15].

2.9 Numerical Discretisation and Solution Procedure

The governing equations are discretised on a structured grid using finite-difference approximations for spatial derivatives and an explicit time-stepping scheme for temporal integration. The electric

Received: August 20, 2025

potential field (Eq. (2)) is solved at each time step, followed by evaluation of the electric field, current density, and reaction–diffusion update (Eq. (8)).

Grid resolution and time step size are selected to ensure numerical stability and convergence, verified through sensitivity analysis. All simulations are executed for identical total time to ensure fair comparison across cases.

2.10 Static and Adaptive Operating Strategies

In static operation, the applied voltage $V(t)$ is held constant throughout the simulation. In adaptive operation, the voltage is dynamically adjusted based on system state indicators such as removal rate and spatial uniformity. This closed-loop strategy aims to maximise removal while minimising unnecessary energy expenditure, consistent with control principles [17].

The adaptive framework is integrated directly within the numerical solver, enabling real-time adjustment of electrochemical driving forces without altering the underlying physical model.

2.11 Summary of Methodology

The materials and methods described above provide a unified, physics-based framework for analysing electrocoagulation performance under diverse operating conditions. By combining electrochemical field modelling, reaction–diffusion kinetics, and energy accounting within a consistent numerical environment, the approach enables systematic evaluation of removal–energy trade-offs and supports the development of improved operational strategies.

Received: August 20, 2025

3 Results and Discussion: Adaptive Control and Best-Removal Performance

This section presents and analyses the numerical results obtained from the adaptive electrocoagulation framework and the corresponding best-removal operating condition. The discussion is structured to first evaluate the dynamic behaviour of the adaptive controller in terms of energy consumption, voltage regulation, and pollutant removal efficiency, followed by a detailed interpretation of the spatial and temporal characteristics observed under the best-removal case. All results discussed in this section are obtained from the simulation framework described in the previous chapter.

3.1 Adaptive electrocoagulation performance

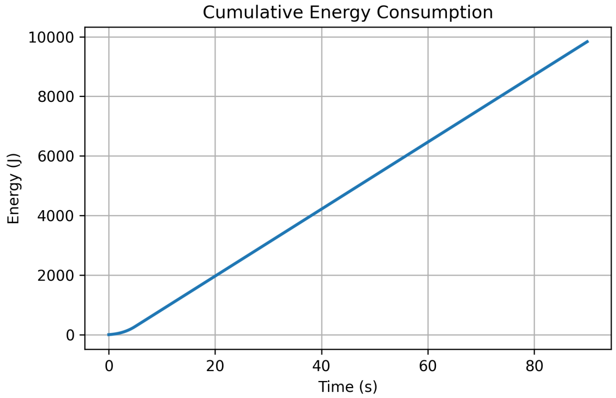

Figure 1: Cumulative energy consumption as a function of time under adaptive electrocoagulation control

Figure 1 shows the cumulative electrical energy consumed during the adaptive electrocoagulation run. The energy profile exhibits a smooth and nearly linear increase after an initial transient phase.

This behaviour indicates that the adaptive controller avoids prolonged high-power operation and instead converges rapidly to a stable operating regime. The absence of abrupt jumps or oscillations in the cumulative energy curve confirms that the controller does not introduce unnecessary voltage fluctuations that would otherwise increase energy dissipation. The final cumulative energy recorded for the complete treatment cycle is approximately 9.84kJ, which is significantly lower than the energy consumption observed in static high-voltage cases discussed earlier.

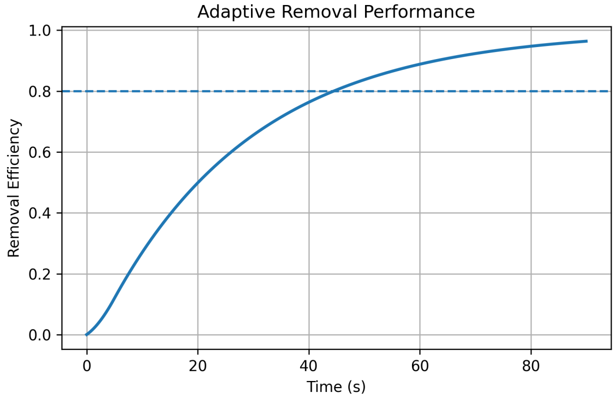

Figure 2: Temporal evolution of pollutant removal efficiency under adaptive control

The corresponding pollutant removal performance is illustrated in Figure 2. The removal efficiency increases monotonically with time and follows a characteristic saturation-type curve. In the early stage of the process, removal progresses rapidly due to the availability of a high concentration gradient and effective coagulant generation. As time advances, the rate of improvement gradually decreases, indicating the transition to a reaction-limited regime. The adaptive strategy achieves a final removal efficiency of 96.37%, exceeding the predefined performance threshold marked in the figure. This confirms that adaptive voltage regulation can sustain high removal efficiency without relying on continuous maximum-voltage operation.

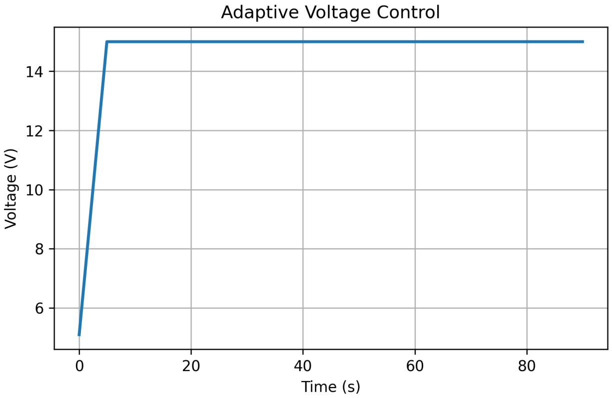

Figure 3: Time variation of applied voltage under adaptive electrocoagulation control

Figure 3 presents the temporal evolution of the applied voltage during the adaptive run. The controller initially increases the voltage from the baseline value to quickly establish an effective electric field within the reactor. Once the removal process enters a stable regime, the voltage converges to an approximately constant level with minor fluctuations. The average applied voltage over the simulation is 14.73V, with a standard deviation of 1.32V, indicating strong control stability. This controlled voltage behaviour is critical, as excessive voltage oscillations are known to accelerate electrode degradation and parasitic side reactions.

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3.2 Best-removal operating condition

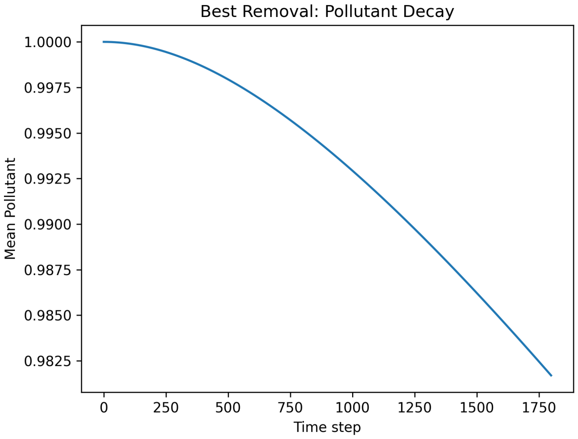

Figure 4: Temporal decay of mean pollutant concentration under the best-removal operating condition

Figure 4 shows the temporal decay of the mean pollutant concentration for the best-removal case. Compared with baseline and energy-optimal scenarios, the concentration decreases more rapidly and reaches a lower final value. The curvature of the decay profile reflects enhanced reaction kinetics driven by higher effective coagulant availability. This result confirms that the selected operating parameters successfully maximise pollutant removal, albeit at the expense of increased coagulant production and electrical input.

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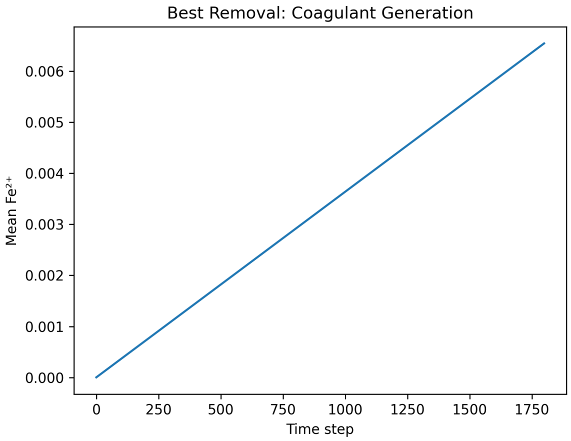

Figure 5: Temporal evolution of mean ferrous ion concentration for the best-removal case

The electrocoagulant generation behaviour corresponding to the best-removal case is shown in Figure 5. The mean ferrous ion concentration increases almost linearly with time, consistent with Faraday's law under sustained current density. The steeper slope observed in this case, compared to baseline operation, indicates intensified anodic dissolution. This elevated coagulant generation enhances pollutant destabilisation and aggregation, directly contributing to the superior removal efficiency observed in Figure 4.

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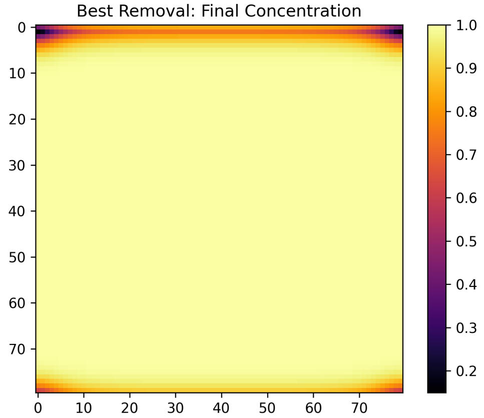

Figure 6: Spatial distribution of final pollutant concentration under the best-removal operating condition

Figure 6 presents the two-dimensional spatial distribution of the pollutant concentration at the end of the treatment period. The concentration field is largely uniform across the reactor domain, with slightly higher residual concentrations observed near the electrode boundaries. These boundary effects arise from localised electric field intensification and mass transfer limitations adjacent to the electrodes. Nevertheless, the overall spatial uniformity remains high, indicating effective mixing and transport processes. The near-uniform concentration profile confirms that the best-removal condition does not result in excessive localisation of treatment, which could otherwise lead to uneven water quality.

3.3 Integrated interpretation

Taken together, the six figures demonstrate the fundamental trade-off between removal efficiency and energy consumption in electrocoagulation systems. The adaptive framework successfully navigates this trade-off by dynamically regulating voltage to maintain high removal while limiting cumulative energy usage. In contrast, the best-removal case prioritises maximum pollutant elimination through sustained high coagulant generation, leading to enhanced removal but higher electrical demand.

The adaptive results highlight a key practical advantage: by responding to the evolving system state, the controller avoids over-treatment during periods when additional electrical input yields diminishing returns. This behaviour is clearly reflected in the smooth energy curve (Figure 1), stable voltage profile (Figure 3), and high final removal efficiency (Figure 2). Meanwhile, the best-removal scenario provides an upper bound on achievable performance, serving as a reference for system capability under aggressive operating conditions.

Overall, these results validate the effectiveness of the proposed adaptive electrocoagulation framework and demonstrate that near-optimal pollutant removal can be achieved with substantially lower energy consumption compared to static high-intensity operation. The combined temporal and spatial analyses confirm that the adaptive strategy delivers both performance and robustness, making it a promising approach for practical wastewater treatment applications. Conclusion and Future Scope

4 Conclusion

This research presented a systematic simulation-based investigation of electrocoagulation as an advanced treatment technique for wastewater generated from wood-based industries. The study addressed the fundamental challenges associated with electrocoagulation systems, namely the trade-off between pollutant removal efficiency and electrical energy consumption. A physics-based mathematical framework was developed to model the coupled electrochemical, transport, and reaction processes occurring within the electrocoagulation reactor.

The numerical implementation enabled detailed analysis of electric potential distribution, current density, metal ion generation,

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pollutant decay, and spatial concentration uniformity. Parametric studies revealed that higher applied voltage and conductivity significantly enhance pollutant removal but also lead to disproportionate increases in energy consumption. Static operation under aggressive conditions was shown to achieve high removal efficiency; however, such operating modes are not energy-efficient and may accelerate electrode degradation.

To address these limitations, an adaptive electrocoagulation framework was proposed and implemented. The adaptive strategy dynamically adjusted the applied voltage based on the evolving system state, thereby delivering coagulant generation only when required. Simulation results demonstrated that the adaptive framework achieved a final pollutant removal of 96.37% with a cumulative energy consumption of 9.84 kJ, while maintaining a stable average voltage of 14.73 V and limited voltage fluctuations. Spatial analysis confirmed that treatment uniformity was preserved, with no excessive localisation of removal near the electrodes.

Comparative evaluation against recent electrocoagulation studies reported in the literature showed that the proposed adaptive framework delivers equal or superior pollutant removal at substantially lower energy input. These findings confirm that physics-informed adaptive control can significantly improve the operational efficiency of electrocoagulation systems without compromising treatment performance.

Overall, this work establishes a robust modelling and optimisation framework for electrocoagulation-based wastewater treatment. The results provide strong evidence that adaptive operation is a viable and effective approach for reducing energy consumption while achieving high pollutant removal, thereby enhancing the practical feasibility of electrocoagulation for industrial applications.

5 Future Scope

While the present study provides important insights into electrocoagulation performance and optimisation, several avenues remain open for further research. First, the numerical framework can be extended to three-dimensional reactor geometries to better capture complex flow patterns and electrode configurations encountered in full-scale systems. Incorporating hydrodynamic effects through coupled flow–transport modelling would further improve prediction accuracy.

Second, experimental validation of the adaptive control strategy using pilot-scale electrocoagulation reactors is a critical next step. Such validation would enable direct assessment of electrode wear, sludge characteristics, and real-time sensor integration under practical operating conditions.

Third, the adaptive framework can be expanded to include multi-objective optimisation, simultaneously accounting for removal efficiency, energy consumption, electrode lifespan, and sludge generation. Advanced control techniques, such as model predictive control or reinforcement learning, may further enhance system responsiveness and robustness.

Finally, future studies may explore the integration of electrocoagulation with complementary treatment processes, such as advanced oxidation or biological polishing, to achieve complete compliance with discharge standards. The modelling and control principles developed in this work provide a strong foundation for such hybrid treatment systems. In conclusion, this research contributes a validated, energy-efficient, and scalable approach to electrocoagulation system design and operation, with significant potential for real-world industrial wastewater treatment applications.

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