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KEY FACTORS AFFECTING THE EFFICIENCY OF ELECTROCOAGULATION IN WASTEWATER TREATMENT

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Abstract:

Electrocoagulation (EC) has emerged as an effective method for wastewater treatment due to its ability to remove a wide range of contaminants with low chemical input. This study provides a comprehensive review of the key factors influencing EC efficiency, including operational parameters, water quality characteristics, and reactor design. The analysis shows that current density, pH, conductivity, electrode material, and electrolysis time play a critical role in determining treatment performance. Under optimized conditions, EC achieves removal efficiencies exceeding 90% for COD, turbidity, and color, while maintaining relatively low sludge production. However, process efficiency varies significantly depending on wastewater composition, requiring system-specific optimization. Performance evaluation highlights the importance of energy consumption and electrode dissolution as key economic factors. Advanced optimization methods, such as Response Surface Methodology, allow identification of optimal operating conditions under multiple interacting variables. Despite its advantages, challenges such as electrode passivation, lack of standardized reactor design, and operational costs limit large-scale implementation. Recent developments focus on hybrid systems and renewable energy integration, which have demonstrated removal efficiencies up to 100% for specific pollutants. Electrocoagulation represents a promising solution for sustainable wastewater treatment, particularly when combined with optimized design and integrated treatment approaches.

Keywords: Electrocoagulation, Wastewater Treatment, Current Density, pH, Conductivity, Electrode Configuration, Reactor Design, Energy Consumption, Pollutant Removal, Hybrid Systems.

Introduction

Water is crucial for life, yet merely around 1% of the world's water resources are accessible as freshwater [1]. With the global population expected to surpass 9 billion by 2045, the strain on these scarce resources is mounting [2]. This issue is especially pressing in dry and semi-dry areas like Uzbekistan, where water shortages, high evaporation rates, and reliance on cross-border rivers exacerbate water stress. In Uzbekistan, rapid urban growth and industrialization have led to increased wastewater production, while the current treatment facilities are limited in both efficiency and reach. Consequently, untreated or inadequately treated wastewater leads to environmental harm, such as salinization, pollution of surface and groundwater, and threats to public health. Thus, effective wastewater treatment is vital for environmental conservation and promoting water reuse in regions with limited water resources [3].

Among available treatment technologies, EC has attracted increasing attention as an effective method. In this process, coagulants are generated in situ through the electrochemical dissolution of sacrificial metal electrodes, typically aluminum or iron [4]. Compared with conventional chemical coagulation, EC achieves high pollutant removal efficiency with reduced chemical consumption and lower sludge production. The formed flocs exhibit good settling properties, which simplifies solid-liquid separation. In addition, EC systems are compact and compatible with renewable energy sources such as solar power, which supports their application in regions with limited infrastructure [5].

Despite these advantages, the performance of electrocoagulation varies significantly across different applications [6]. This variation is mainly associated with the diversity of wastewater composition, which depends on the source, such as textile, car wash, dairy, or pharmaceutical effluents. At the same time, EC efficiency is strongly influenced by key operating parameters, including pH, current density, electrode material, conductivity, and electrolysis time. These parameters control coagulant generation, pollutant destabilization, floc formation, and energy consumption. As a result, optimal conditions for one type of wastewater are not directly transferable to another.

A major limitation in large-scale implementation of electrocoagulation is the absence of a systematic approach to reactor design and process optimization. Most studies focus on specific pollutants or individual operating conditions, while limited attention is given to the combined effect of multiple parameters. Since process conditions must be adjusted for each wastewater type, a factor-based analysis is required to establish consistent design guidelines and improve process predictability [7].

The aim of this study is to provide a comprehensive analysis of electrocoagulation and to evaluate the influence of operating parameters on treatment efficiency. The work focuses on key factors such as current density, pH, electrode configuration, conductivity, electrolysis time, and mixing conditions. Special attention is given to wastewater characteristics relevant to regions such as Uzbekistan, where high salinity and variable pollution loads require adaptable treatment approaches. In addition, key challenges, including electrode passivation and energy consumption, are discussed. Recent developments in hybrid electrocoagulation systems are also considered as potential approaches to improve treatment performance across different wastewater types.

Fundamentals of Electrocoagulation

EC is an electrochemical process based on electrolysis, where coagulants are generated in situ through the dissolution of sacrificial electrodes. In contrast to conventional chemical treatment, EC integrates electrochemical reactions, coagulation, and flotation within a single system.

An EC system consists of an electrolytic cell with an anode and a cathode immersed in wastewater and connected to a direct current (DC) power supply. The process involves three main stages.

During anodic oxidation, the sacrificial electrode, typically aluminum or iron, dissolves and releases metal ions into the solution:

$Al \rightarrow Al^{3+} + 3e^-$

$Fe \rightarrow Fe^{2+} + 2e^-$

At the cathode, water reduction produces hydrogen gas and hydroxide ions:

$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$

The generated metal ions react with hydroxide ions to form metal hydroxides such as $Al(OH)_3$ and $Fe(OH)_3$. These species act as coagulants, destabilizing suspended particles, emulsions, and colloids (Fig. 1).

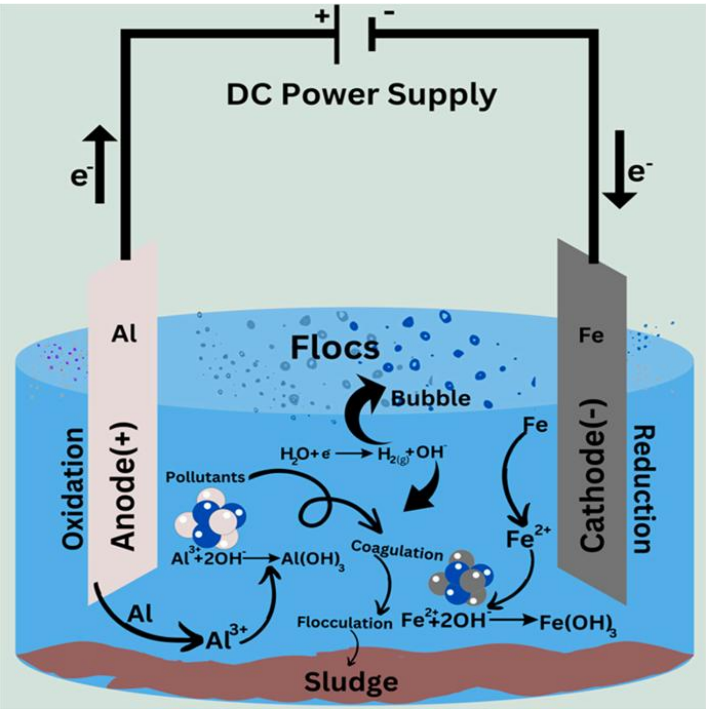

Figure 1. Systematic representation of the electrocoagulation process, including anodic dissolution, cathodic reactions, formation of metal hydroxides, flocculation, and pollutant removal mechanisms.

Floc formation occurs when these hydroxides adsorb dissolved and particulate pollutants, forming larger aggregates with high settling capacity.

The amount of dissolved metal is controlled by Faraday's law:

$$m = \frac{I \cdot t \cdot M_w}{z \cdot F}$$

where:

m- mass of dissolved metal (g)

I - current (A)

t - time (s)

M_w*- molar mass of electrode material (g/mol)*

z - number of electrons involved

F - Faraday constant (96485 C/mol)

This relationship shows that coagulant dosage depends directly on current and electrolysis time. As a result, the process allows precise control of treatment intensity through electrical parameters.

Pollutant removal occurs through two main physical mechanisms. Sedimentation removes dense flocs that settle at the bottom of the reactor, while electroflotation removes lighter flocs that attach to hydrogen bubbles and rise to the surface.

EC provides several operational advantages. The process does not require external chemical addition, which reduces secondary pollution. High removal efficiency is achieved for colloids, suspended solids, and organic contaminants due to effective charge neutralization and adsorption. The system design remains simple and flexible, and it can be integrated with renewable energy sources in decentralized applications.

The effectiveness of EC depends on key parameters such as current density, pH, conductivity, electrode material, and electrolysis time. These factors control coagulant generation, floc structure, and overall process efficiency.

Methods

This study uses a systematic literature review to analyse the main factors that affect the efficiency of the electrocoagulation (EC) process in wastewater treatment. As this is a review paper, no primary experimental data were generated. Instead, the analysis is based on secondary data synthesised from peer-reviewed scientific publications.

A total of 16 relevant studies published between 2001 and 2025 were selected through targeted searches of academic databases. The selection criteria included relevance to electrocoagulation technology and a focus on operational parameters, water quality characteristics, reactor design, performance evaluation, optimisation techniques and challenges associated with the process. Priority was given to articles published in high-impact journals and to studies that provided quantitative data on pollutant removal efficiency, energy consumption and electrode consumption.

The reviewed literature covers a wide range of wastewater types, including textile, hospital, saline, dairy and industrial effluents. Particular attention was paid to studies conducted under conditions relevant to arid and semi-arid regions, such as those characterised by high salinity and variable pollution loads.

Data extraction and synthesis were performed systematically. The key parameters examined included current density, electrolysis time, initial pH, solution conductivity, temperature, electrode material and configuration, inter-electrode spacing, mixing conditions and wastewater composition. Performance indicators such as removal efficiency (COD, turbidity, colour and total dissolved solids), energy consumption (kWh/m^3), electrode dissolution rate and sludge characteristics were collected and compared across different studies.

Optimisation approaches, particularly Response Surface Methodology (RSM) combined with Central Composite Design (CCD) and Analysis of Variance (ANOVA), were analysed to identify significant variables and their interactions. Qualitative and quantitative findings from individual studies were synthesised critically to reveal common trends, optimal operating ranges, contradictions and research gaps.

All interpretations and conclusions drawn in this review are supported by the original references cited throughout the text. This methodological approach provides a comprehensive understanding of the electrocoagulation process, highlighting its potential and limitations for practical implementation in wastewater treatment systems.

Results and Discussion

Operational Factors Affecting Electrocoagulation Efficiency

The efficiency of EC is governed by a range of interconnected operational parameters. These factors control coagulant generation, floc formation, and energy consumption, and must be adjusted according to wastewater characteristics to achieve optimal performance.

Current density and applied voltage. Current density (CD), defined as the current per unit electrode area, is one of the most influential parameters in EC. It determines the rate of anodic dissolution, coagulant generation, gas bubble production, and floc growth [8].

Higher current density increases the release of metal ions and promotes the formation of metal hydroxide flocs, which enhances pollutant removal. At the same time, excessive current results in energy losses as heat, reduces process stability, and significantly increases operational costs. Therefore, an optimal current density is required to balance efficiency and energy consumption [9].

Experimental studies show that removal efficiency increases with current density up to an optimum value (e.g., around 2 mA/cm^2), after which no significant improvement is observed while energy consumption increases (Fig. 2).

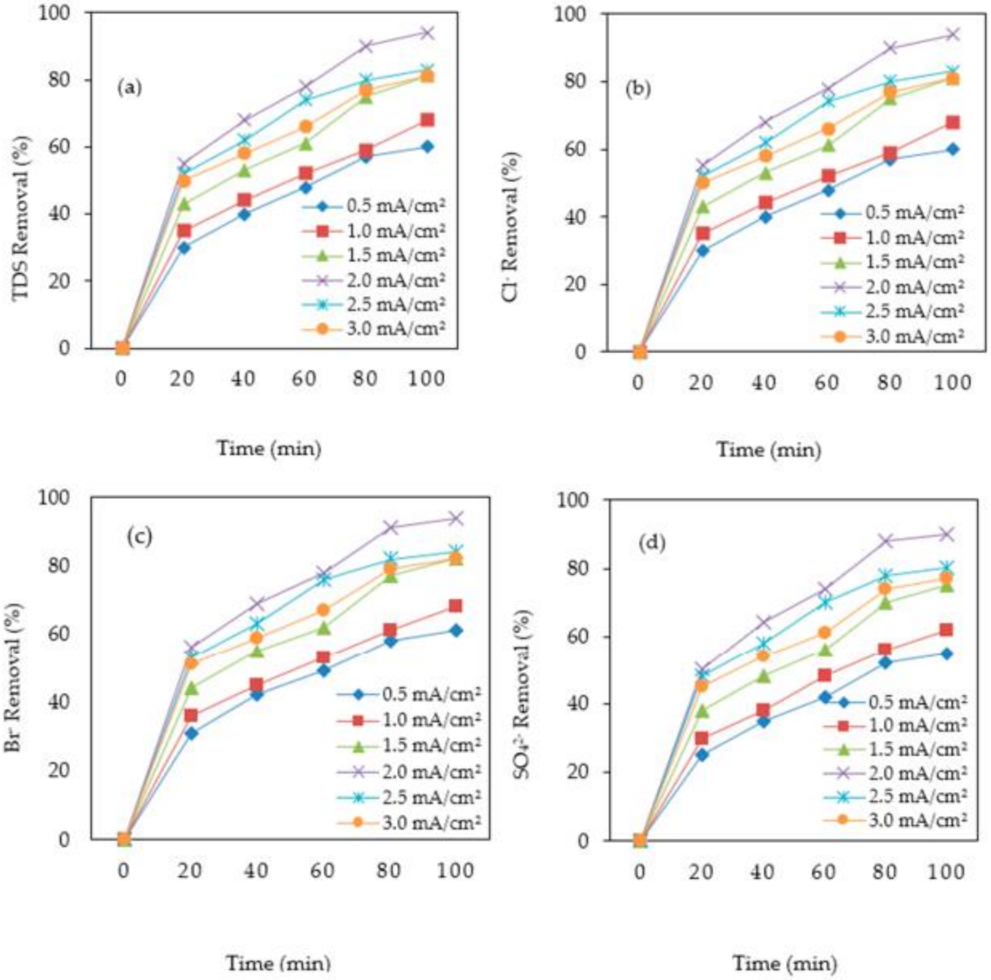

Figure 2. Effect of current density and electrolysis time on pollutant removal efficiency in electrocoagulation.

Electrolysis and operating time. Electrolysis time directly influences treatment performance by controlling the total amount of coagulant generated. Longer operation increases metal ion release and floc formation, leading to improved pollutant removal.

Removal efficiency typically rises with time until an optimal point is reached, after which the removal rate remains constant because sufficient flocs are already available [10]. For example, in saline water treatment, 80 minutes was identified as an optimal time to balance removal efficiency with power consumption.

Electrode material and arrangement. Electrode material plays a key role in determining treatment efficiency. Aluminum and iron are widely used due to their availability and performance. Aluminum is often more effective for the removal of oils and organic compounds, while iron can offer economic advantages in certain applications.

Electrode configuration also affects performance. Monopolar arrangements (parallel or series) are commonly used due to lower energy consumption, whereas bipolar configurations can enhance removal efficiency under specific conditions. Different electrode configurations influence current distribution and energy consumption, as illustrated in Fig. 3.

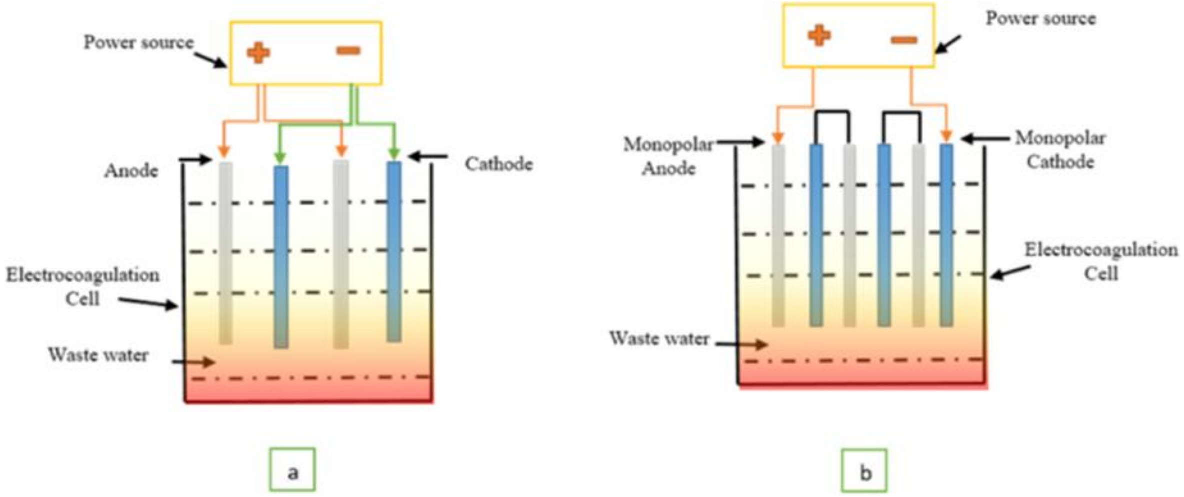

Figure 3. Batch reactor for electrocoagulation: a) monopolar electrode reactor connected in parallel, b) monopolar electrode reactor connected in series [11].

Inter-electrode spacing. The distance between electrodes affects electrical resistance and ion transport within the reactor. Smaller spacing reduces Ohmic losses and lowers energy consumption.

However, excessively small spacing may disrupt floc formation due to strong electrostatic interactions, while large spacing reduces ion mobility and decreases treatment efficiency. Optimal spacing is typically within the range of 3-20 mm [12].

Mixing speed. Mixing enhances mass transfer and promotes uniform distribution of coagulants and pollutants. Proper agitation improves floc formation and increases removal efficiency.

Excessive mixing generates shear forces that break flocs into smaller particles, which reduces separation efficiency.

Electrode passivation. Electrode passivation is a major operational limitation.It occurs when insulating layers, such as metal oxides or mineral deposits, form on the electrode surface.

This layer reduces current efficiency, limits metal ion release, and increases energy consumption. Passivation leads to a decline in pollutant removal efficiency and is often associated with calcium carbonate and metal oxide deposition.

Common mitigation methods include electrode cleaning, polarity reversal, and mechanical treatment [13].

These operational parameters are strongly interdependent, and their combined optimization is required to achieve stable and energy-efficient electrocoagulation performance.

Water Quality Factors Affecting Electrocoagulation Efficiency

The efficiency of electrocoagulation is strongly influenced by the physicochemical properties of wastewater. These factors determine coagulant speciation, reaction kinetics, energy demand, and the stability of the process (Emamjomeh & Sivakumar, 2009; Mousazadeh et al., 2021).

Initial pH of the solution. The initial pH is one of the most critical parameters, as it controls both coagulant formation and pollutant removal mechanisms.pH determines whether soluble or insoluble metal hydroxide species are formed. In aluminum-based systems, Al^{3+} ions dominate at pH below 3.5, while insoluble $Al(OH)_3$ flocs form in the pH range of 4-9.5 and provide the highest adsorption capacity[14].

The distribution of aluminum species strongly depends on pH, with $Al(OH)_3$ dominating in the neutral range, which corresponds to maximum coagulation efficiency (Fig.4).

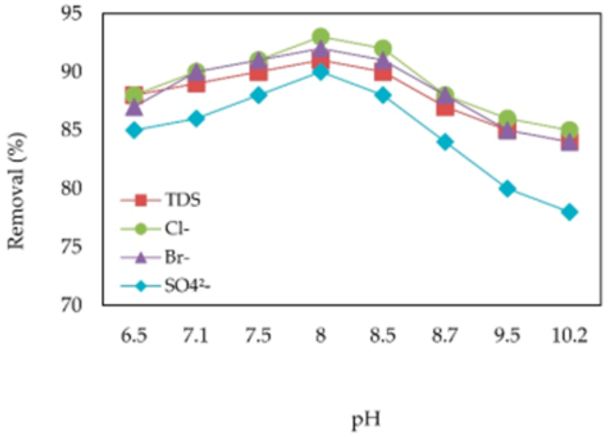

Figure 4. Distribution of aluminum species as a function of pH and its effect on coagulation efficiency.

During EC, the system often exhibits a buffering effect, where pH shifts toward neutral conditions. The distribution of aluminum species as a function of pH clearly shows that Al $(OH)_3$ dominates in the neutral range, which corresponds to maximum coagulation efficiency (Fig. 5).

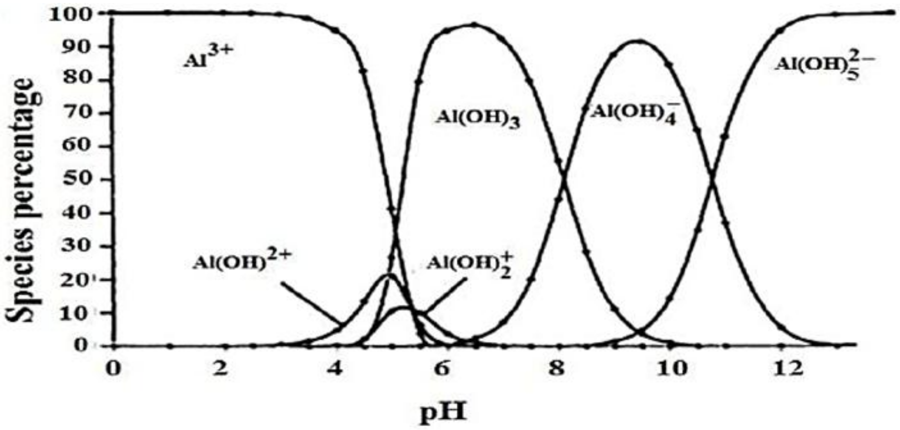

Figure 5. Impact of pH on the formation of aluminum hydroxide species and flocs.

At pH above 10, soluble Al $(OH)_4^-$ species dominate, which do not contribute to coagulation and lead to reduced removal efficiency for COD and color.

During EC, the solution tends to shift toward neutral pH due to simultaneous anodic and cathodic reactions.

Solution conductivity. Conductivity determines the ability of the solution to carry electric current. Higher conductivity reduces electrical resistance and lowers energy consumption. However, high conductivity can increase current density and electrode consumption, which reduces current efficiency and increases energy demand. It also improves process stability by maintaining uniform current distribution.

Supporting electrolytes such as NaCl are often added to increase conductivity and reduce electrode fouling. Excessively high conductivity increases electrode dissolution rates and operating costs, and may lead to unstable current conditions.

Temperature. Temperature affects reaction kinetics, ion mobility, and electrochemical efficiency. An increase in temperature enhances molecular movement and collision frequency, which improves floc formation and pollutant removal [15].

Current efficiency increases with temperature up to moderate levels, as higher temperatures reduce the formation of passive oxide layers on electrode surfaces. Maximum current efficiency is typically observed at temperatures up to 60°C, after which performance declines.

At elevated temperatures, floc stability decreases, and aggregation is disrupted, which reduces sedimentation efficiency.

A schematic representation of the interaction between operational parameters, water quality factors, and electrocoagulation mechanisms is presented in Fig. 6.

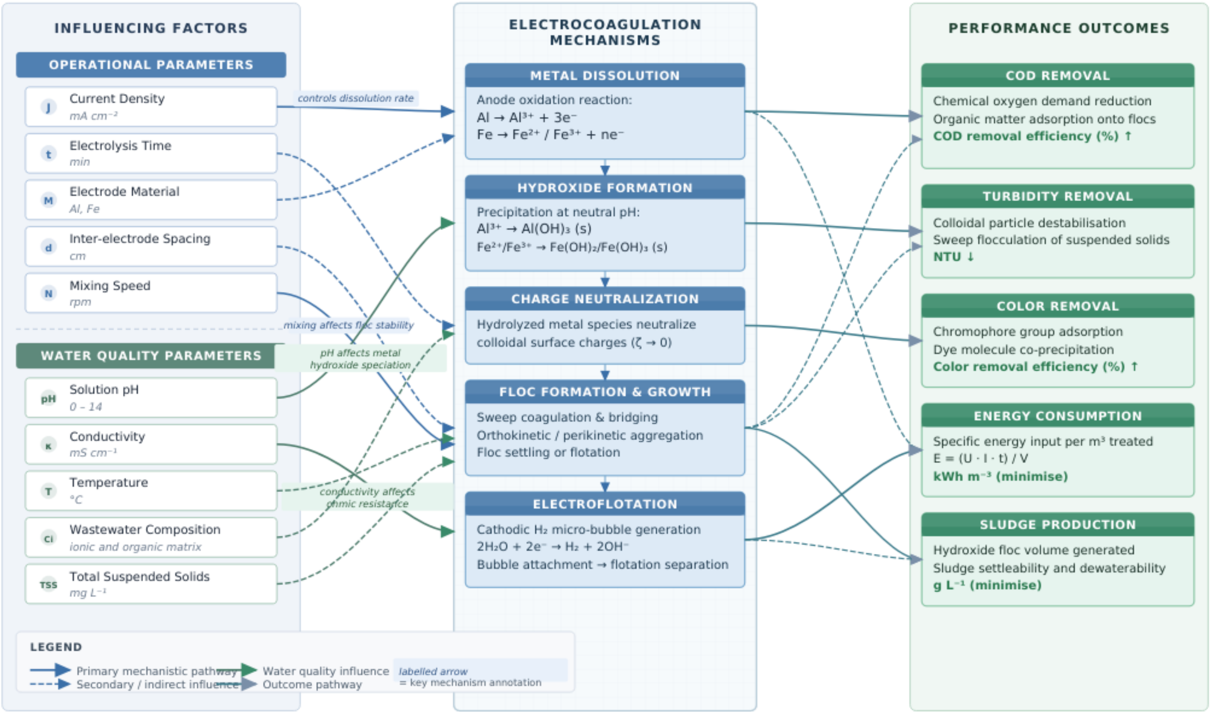

Figure 6. Interaction between operational parameters, water quality factors, electrocoagulation mechanisms, and treatment performance outcomes.

Wastewater composition and pollutant nature. The composition of wastewater directly influences electrocoagulation performance. The presence of multivalent ions such as Ca^{2+} and Mg^{2+} promotes the formation of insulating layers on electrode surfaces, leading to passivation, increased energy consumption, and reduced metal dissolution rates.

High initial pollutant concentrations require higher coagulant dosage, which must be achieved by adjusting current density or treatment time.

Wastewater from different sources, including textile, dairy, and pharmaceutical industries, exhibits significant variation in chemical composition. Therefore, process parameters must be adapted for each specific case. This variability explains why optimal operating conditions differ significantly between wastewater types and highlights the need for site-specific optimization [16].

Suspended solids (TSS). The concentration of suspended solids affects floc formation and separation behavior. Moderate levels of suspended solids enhance coagulation by providing additional surfaces for adsorption and aggregation. This effect enhances collision probability between particles and coagulants, improving removal efficiency. High TSS concentrations increase sludge production and complicate solid-liquid separation, which requires additional handling and treatment.

These water quality factors interact with operational parameters and must be considered together to achieve stable and efficient electrocoagulation performance.

Reactor and Electrode Design Factors

The design of the reactor and electrode configuration strongly influences the efficiency, stability, and economic performance of electrocoagulation systems. The absence of standardized design criteria makes comparison between systems difficult and highlights the importance of understanding key design parameters.

Electrode arrangement

The electrical connection of electrodes determines current distribution, potential requirements, and system efficiency.

Monopolar parallel (MP-P): All anodes are connected to the positive terminal and all cathodes to the negative terminal. Current is distributed among electrodes based on individual resistance. This configuration is widely reported as the most cost-effective for both aluminum and iron electrodes.

Monopolar series (MP-S): Electrodes are connected in series, leading to higher total resistance and increased voltage requirements. This configuration results in higher energy consumption compared to parallel systems.

Bipolar parallel (BP-P): Only the outer electrodes are connected to the power supply, while internal electrodes become polarized during operation. This configuration can enhance pollutant removal efficiency due to multiple reaction zones but generally increases operational cost.

Reactor Geometry and System Types

Reactor design affects hydrodynamics, mass transfer, and operational stability.

Batch reactors: Commonly used in laboratory studies. Operating conditions change over time, which affects reproducibility and process control.

Continuous reactors: Preferred in industrial applications due to stable operating conditions and consistent coagulant production.

Specialized reactor designs: Press-filter reactors with integrated membranes for simplified separation. Rotating cylinder reactors to enhance mass transfer and reduce electrode fouling. Fluidized bed reactors with increased surface area for improved removal efficiency. Continuous flow reactors with structured electrodes to enhance pollutant removal in dynamic systems.

Electrode Material and Shape

Electrode properties determine coagulant type, dissolution behavior, and treatment performance.

Material selection: Aluminum and iron are the most commonly used materials due to availability, cost, and efficiency[5]. Aluminum is often more effective for removing oils and organic compounds, while iron provides cost advantages. Hybrid systems combining Al and Fe improve performance in complex wastewater systems.

Inert materials: Graphite or titanium-based electrodes are used as cathodes in waters with high Ca^{2+} and Mg^{2+} concentrations to reduce scaling and passivation.

Electrode shape: Flat plates are the most common configuration. Alternative geometries such as mesh, rods, or packed materials increase surface area and improve mass transfer.

Inter-electrode spacing (IED)

Electrode spacing affects electrical resistance, ion transport, and floc formation[9].

Smaller spacing reduces Ohmic losses and lowers energy consumption, which is particularly important for low-conductivity wastewater. This effect becomes critical when electrical resistance dominates system performance.

However, excessively small spacing (less thn 3 mm) can disrupt floc formation due to strong electrostatic interactions, while larger spacing slows ion transport and reduces treatment efficiency. Optimal spacing is typically in the range of 1-2 cm, which allows effective floc growth and stable operation.

Scale-up factors

Scaling electrocoagulation from laboratory to industrial systems requires maintaining key physical and electrochemical relationships. Among these factors, the surface area to volume ratio (S/V) is particularly critical, as it directly affects current density, bubble formation, and coagulant dosing.

Surface area to volume ratio (S/V): Electrode surface area controls current density and coagulant dosage. Higher S/V ratios improve treatment efficiency but require adjustment of current density.

Dimensionless parameters: Scale-up requires maintaining similarity in hydrodynamic and transport conditions, including Reynolds number (flow regime), Froude number (buoyancy effects), and Weber number (surface tension effects). These parameters ensure consistent performance across different reactor sizes.

Performance Evaluation and Optimization of Electrocoagulation

The evaluation and optimization of electrocoagulation systems are essential for scaling from laboratory studies to industrial applications. Performance is assessed using both environmental and economic indicators, while optimization focuses on identifying optimal operating conditions under interacting parameters.

Performance evaluation metrics

Removal efficiency (RE%). Removal efficiency is calculated by comparing initial and final concentrations of pollutants such as Chemical Oxygen Demand (COD), turbidity, color, and Total Dissolved Solids (TDS) (Chen, 2004). Under optimized conditions, EC achieves removal efficiencies exceeding 90% for COD and color in various wastewater types[9].

Energy consumption. Energy consumption is expressed in kWh/m^3 or kWh/kg of pollutant removed and is a key factor in economic feasibility. For example, saline water treatment using EC reported energy consumption as low as 0.21 kWh/m^3, which is lower than many conventional methods such as reverse osmosis.

Electrode consumption. Electrode consumption is defined as the mass of dissolved sacrificial material and is evaluated using Faraday's law. The comparison between theoretical and experimental values determines current efficiency.

Operational cost (OC). Operational cost includes electricity usage, electrode consumption, chemical additives, and sludge management. This parameter integrates both technical and economic aspects of EC performance.

Sludge characteristics. EC produces lower sludge volumes compared to chemical coagulation. The sludge exhibits improved settling and dewatering properties, reducing handling requirements.

Optimization Methodologies

Response Surface Methodology (RSM). RSM is widely applied to evaluate the influence of multiple variables and to identify optimal operating conditions with a reduced number of experiments. It allows simultaneous optimization of removal efficiency and energy consumption.

Central Composite Design (CCD). CCD is used within RSM to model interactions between variables such as pH, current density, and electrolysis time using quadratic regression models.

Analysis of Variance (ANOVA). ANOVA determines the statistical significance of individual parameters and their interactions, ensuring model reliability.

Desirability function. This method converts multiple objectives, such as maximizing removal efficiency and minimizing operational cost, into a single optimization criterion.

Key Findings in Optimization Studies

Hospital wastewater. Optimal conditions achieved 92.3% color removal and 95.3% COD removal at pH 7.5 with a treatment time of 60 minutes using aluminum electrodes[9].

Textile wastewater. Optimal parameters were pH 9, voltage 4 V, and electrolysis time ~36 minutes, resulting in >99% color removal and >96% turbidity.

Saline water. Optimal conditions included current density 2 mA/cm^2, pH 8, and 80 minutes of operation, achieving >90% removal of TDS, chloride, and sulfate.

Hybrid systems. Hybrid electrocoagulation systems combined with processes such as electro-Fenton or ozonation achieved up to 100% removal of turbidity and color in textile.

Table 1. Summary of key parameters influencing electrocoagulation efficiency.

Parameter	Effect on EC process	Impact on efficiency	Reference
Current density	Controls rate of metal dissolution and bubble generation	↑ increases removal, but excess → ↑ energy consumption *(optimum ~1-20 mA/cm^2; >90% COD removal)*	[4], [9]
Electrolysis time	Determines total coagulant dosage	↑ improves removal until optimum, then no significant change *(optimum 10-60 min)*	[7], [9]
pH	Controls metal hydroxide speciation	Optimal (4-9) → maximum coagulation efficiency *(peak ~6-8)*	[4], [5]
Conductivity	Affects electrical resistance	↑ reduces energy consumption, improves stability *(0.2-2 kWh/m^3 typical range)*	[6], [9]
Electrode material	Determines type of coagulant formed	Al → better for organics, Fe → cost-effective *(COD removal 80-95%)*	[5], [9]
Electrode spacing	Influences Ohmic resistance and ion transport	Too small → floc breakage, too large → low efficiency *(optimal 0,3-2 cm)*	[4], [6]
Temperature	Affects reaction kinetics and ion mobility	Moderate ↑ improves efficiency, high → floc instability *(optimal ~20-60°C)*	[9]
Mixing speed	Controls mass transfer and floc formation	Optimal mixing → better removal, high → floc breakage *(~100-300 rpm typical)*	[7]
Wastewater composition	Determines reaction pathways	High Ca^{2+}/Mg^{2+} → passivation, complex matrix → lower efficiency *(efficiency drop observed in hard water)*	[6], [9]
TSS	Influences floc formation and settling	Moderate → improves removal, high → sludge increase *(turbidity removal >90-95%)*	[5]

Challenges and Limitations

Despite its effectiveness, large-scale implementation of electrocoagulation faces several technical and economic limitations.

Lack of systematic design. There is no universal design methodology for EC reactors, which limits comparability between studies and complicates scale-up from laboratory to industrial systems. Reactor performance often depends on case-specific configurations and operating conditions.

Electrode passivation. Passivation is a critical operational issue. Insulating layers such as calcium carbonate or magnesium hydroxide form on electrode surfaces, reducing current efficiency and metal ion release. This increases energy consumption and decreases pollutant removal efficiency.

High operating costs. Energy consumption remains a major cost factor in EC systems. Continuous electrical input increases operational expenses. In addition, sacrificial electrodes dissolve during operation and require periodic replacement, contributing to maintenance costs.

Sludge management. Although EC produces less sludge than chemical coagulation, sludge handling remains a challenge. The sludge contains dissolved electrode material and adsorbed pollutants, which require proper treatment, disposal, or reuse.

Water quality constraints. Efficient EC operation often requires sufficient conductivity to minimize electrical resistance. Low-conductivity wastewater increases energy demand. In some cases, EC treatment leads to increased concentrations of secondary species such as chloride ions or residual aluminum, which require additional treatment.

Complexity of wastewater composition.EC performance varies significantly depending on wastewater characteristics. Parameters such as pH, pollutant type, initial concentration, and the presence of interfering ions require system-specific optimization. This limits the direct transfer of operating conditions between different applications.

Future Perspectives

Current research trends focus on improving efficiency, reducing costs, and expanding the application range of electrocoagulation.

Hybrid and integrated systems. Integration of EC with other treatment technologies improves overall performance. Coupling with advanced oxidation processes such as electro-Fenton, ozonation, or UV irradiation has achieved up to 100% removal of turbidity and color in complex wastewater. Integration with membrane processes reduces fouling and enhances treatment efficiency.

Renewable energy integration. To reduce operational costs and environmental impact, EC systems are increasingly combined with renewable energy sources such as solar panels and wind. This approach is particularly relevant for remote or water-scarce regions.

Mathematical modeling and optimization. Modern research applies statistical tools such as Response Surface Methodology (RSM) and Central Composite Design (CCD) to model interactions between parameters such as pH, current density, and time. These approaches improve process predictability and support optimization.

Treatment of emerging pollutants. EC is increasingly applied to remove emerging contaminants such as microplastics and nanoparticles. Removal efficiencies above 95% have been reported for nanoparticle systems.

Sludge valorization. Recent studies explore the reuse of EC sludge in applications such as fertilizers, construction materials, and catalysts. This approach reduces disposal costs and improves process sustainability.

Portability and system flexibility. Advances in reactor design enable the development of compact and modular EC systems. These units allow real-time monitoring of voltage and current, improving process control and adaptability for different wastewater type.

Conclusion

Electrocoagulation is an effective technology for wastewater treatment, capable of achieving high removal efficiencies exceeding 90% for COD, turbidity, and color under optimized conditions. The process combines electrochemical reactions and coagulation, which reduces chemical consumption and sludge production.

The efficiency of electrocoagulation depends on key parameters such as current density, pH, conductivity, electrode material, and electrolysis time. These factors control coagulant generation, floc formation, and energy consumption. Optimal conditions are not universal and must be adjusted for each type of wastewater.

Despite its advantages, large-scale application remains limited due to electrode passivation, high energy demand, operational costs, and the absence of standardized reactor design.

Future development should focus on hybrid systems, renewable energy integration, and advanced optimization methods. These approaches have demonstrated removal efficiencies approaching 100% for specific pollutants, indicating strong potential for industrial application and sustainable water management.

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