Larhyss Journal, ISSN 1112-3680, n°65, Mars 2026, pp. 171-191
© 2026 All rights reserved, Legal Deposit 1266-2002

REVOLUTIONIZING WATER TREATMENT APPLICATION OF ELECTROCOAGULATION FOR INDUSTRIAL WASTEWATER USING OPTIMIZED ELECTRODE CONFIGURATIONS

SIKDAR P.[1], KUMAR V.H.[2*], MEHTA D.[3], MANAS D.[4], RATHORE K.[5]

[1]Assistant Professor, Civil Engineering Department, Rungta International Skills University, Bhilai, Chhattisgarh, 490024, India
[2*]Assistant Professor, Electrical Engineering Department, Rungta International Skills University, Bhilai, Chhattisgarh, 490024, India
[3]Assistant Professor, Civil Engineering Department, Dr. S. & S. S. Ghandhy Government Engineering College, Surat, Gujarat, 395001, India
[4]Assistant Professor Civil Engineering Department Shri Shankaracharya Institute of Professional Management and Technology Raipur (C.G.), India 492015.
[5]Assistant Professor, Civil Engineering Department, Rungta International Skills University, Bhilai, Chhattisgarh, 490024, India

(*) v.hemant.kumar@rungta.org

Research Article – Available at http://larhyss.net/ojs/index.php/larhyss/index
Received October 2, 2025, Received in revised form March 2, 2026, Accepted March 3, 2026

ABSTRACT

Industrial wastewater contains complex mixtures of organic pollutants, heavy metals, dyes, oils, and suspended solids that challenge conventional treatment processes. This study evaluates the effectiveness of electrocoagulation (EC) for treating real industrial effluents, with specific attention to the role of electrode material combinations and configuration. Experiments were conducted using a custom-designed 5 L batch EC reactor operated at laboratory scale under a static flow regime with parallel electrode orientation. Three representative wastewaters from textile manufacturing, petroleum refining, and metal processing industries were treated using different aluminum-iron electrode combinations, spacings, and arrangements. Parametric analysis indicated that alternating aluminum and iron electrodes provided favorable coagulation behavior and stable operation across the tested wastewaters. The reported chemical oxygen demand (COD) removal efficiencies (90.3-93.8%) and heavy metal removal efficiencies for lead and chromium (95.1-97.6%) correspond to the best-performing operating conditions identified for each wastewater type, rather than uniform performance across all cases. These efficiencies were achieved at moderate current densities, with energy consumption remaining below 0.8 kWh m^{-3}, which is comparable to or lower than values commonly reported for conventional EC systems and other advanced physicochemical treatment methods. Electrode spacing in the range of 1.0-1.5 cm enhanced treatment efficiency while limiting energy demand and electrode passivation. Compared to chemical coagulation, EC generated approximately 50% less sludge with improved dewaterability. While the results demonstrate strong treatment potential, practical considerations related to electrode longevity, maintenance requirements, and continuous-flow operation must be addressed for scale-up. Overall, the findings confirm that appropriately selected aluminum–iron electrode arrangements can effectively treat diverse industrial wastewaters under optimized conditions.

Keywords: Electrocoagulation, Electrode configuration, Industrial wastewater treatment, Heavy metals removal, Optimization, Sludge management.

Abbreviation

EC	Electrocoagulation
DEP	Dielectrophoretic / Dielectrophoresis
COD	Chemical Oxygen Demand
BOD	Biological Oxygen Demand
TOC	Total Organic Carbon
AOPs	Advanced Oxidation Processes
APHA	American Public Health Association
DC	Direct Current
Al	Aluminum
Fe	Iron
MP–P	Monopolar–Parallel Configuration
BP	Bipolar Configuration
HDPE	High-Density Polyethylene
NTU	Nephelometric Turbidity Unit
ANOVA	Analysis of Variance
R^2	Coefficient of Determination
kWh/m^3	Kilowatt-hour per cubic meter
lpcd	Liters per Capita per Day
C.G.	Chhattisgarh
MoEF	Ministry of Environment and Forests
MCM	Million Cubic Meters

INTRODUCTION

Rapid industrialization over recent decades has delivered substantial economic and social benefits; however, it has also intensified environmental pressures, particularly through the generation and discharge of complex industrial wastewaters. Effluents from sectors such as textiles, electroplating, pulp and paper, petrochemicals, and food processing typically contain a heterogeneous mixture of synthetic dyes, detergents, emulsified oils, suspended solids, toxic metal ions, and other refractory organic compounds. The diversity and persistence of these pollutants complicate wastewater treatment and pose serious risks to aquatic ecosystems and human health (Verma et al., 2024; Ghernout and Elboughdiri, 2020).

Many of these contaminants are inherently resistant to conventional treatment processes. Synthetic dyes are designed for chemical stability, detergents and surfactants interfere with oxygen transfer, and emulsified oils form stable dispersions that are difficult to separate. In addition, heavy metals such as cadmium, chromium, and lead are non-biodegradable and tend to accumulate in biological systems, leading to long-term ecological and health impacts (Tolkou et al., 2021; Yadav et al., 2024; Moradi et al., 2025). Adsorption-based approaches, including activated carbon systems for mercury removal, have also been investigated as alternative treatment options (Masmoudi et al., 2018). Various adsorption-based strategies have been investigated for metal removal, including natural bentonite materials, yet process efficiency and sludge management remain practical challenges (Ghomri et al., 2013). Variations in effluent pH further exacerbate treatment challenges by affecting both pollutant toxicity and process performance (Waghmare and Arfin, 2015).

Conventional biological treatment systems, including activated sludge processes, often struggle to effectively treat such complex wastewaters. The presence of toxic, inhibitory, or non-biodegradable compounds can suppress microbial activity, resulting in reduced treatment efficiency and difficulty in meeting increasingly stringent discharge and reuse standards (Unde et al., 2018; Ying Shi et al., 2020; Chadee et al., 2024).

In response to these limitations, electrocoagulation (EC) has gained increasing attention as an alternative and complementary treatment technology. EC involves the in-situ generation of coagulant species through the electrolytic dissolution of sacrificial metal electrodes, typically aluminum or iron, enabling the destabilization and removal of a broad range of organic and inorganic contaminants via aggregation, sedimentation, or flotation (Tellez and Wolff, 2016). The process is recognized for its operational simplicity, relatively short treatment times, and reduced dependence on chemical additives (Choksi et al., 2015b).

However, EC performance is strongly influenced by operational parameters such as electrode material, configuration, current density, pH, and treatment duration. Suboptimal electrode arrangements can lead to uneven current distribution, increased energy consumption, and reduced pollutant removal efficiency (Choksi et al., 2015a; Pandety et al., 2025). Therefore, systematic evaluation and optimization of electrode configurations are essential, particularly for improving process efficiency and facilitating scale-up for industrial applications.

Against this background, the present study investigates the effectiveness of electrocoagulation for treating industrial wastewater, with a specific emphasis on optimizing electrode configurations. The study examines the influence of electrode arrangement on pollutant removal efficiency, energy consumption, and sludge characteristics, while also assessing the adaptability of the process to effluents with varying compositions. The findings aim to provide practical guidance for the design of efficient, cost-effective EC systems that support regulatory compliance, water reuse, and sustainable industrial wastewater management.

PRINCIPLES AND THE ROLE OF ELECTRODE OPTIMIZATION

Industrial wastewater often contains complex mixtures of organic and inorganic contaminants that challenge the efficiency of conventional treatment technologies. Established methods such as chemical coagulation-flocculation, membrane filtration, and advanced oxidation processes (AOPs) have been widely implemented; however, each is associated with notable shortcomings (Sbai and Loukli, 2015; Achour and Chabbi, 2017; Achour et al., 2017). Coagulation-adsorption treatment systems, while effective for nutrient and contaminant removal, still require chemical dosing and sludge handling, raising operational and disposal concerns (Kheliel et al., 2015). Chemical coagulation, for example, requires the continual addition of reagents, which not only increases operational costs but also results in substantial sludge generation that demands further disposal and treatment (Mollah et al., 2004; Verma et al., 2019). Conventional adsorption-coagulation systems have also demonstrated effectiveness for organic matter removal, but often result in significant sludge production and secondary waste management requirements (Achour et al., 2002; Guergazi et al., 2013; Ghecham et al., 2018).

Membrane filtration, while effective in producing high-quality effluent, is prone to severe fouling, leading to reduced flux, frequent cleaning requirements, and costly membrane replacement (Sivakumar et al., 2015; Ahmad et al., 2020). Similarly, AOPs, although capable of degrading persistent pollutants, are energy-intensive and often require expensive catalysts or oxidants, making them less viable for large-scale applications with fluctuating influent compositions (Ghernaout and Elboughdiri, 2020; Oturan and Aaron, 2014). These drawbacks underscore the need for innovative, sustainable, and cost-effective treatment methods that can adapt to the variability of industrial effluents (Kumar and Pal, 2021; Patel et al., 2022).

Electrocoagulation (EC) has emerged as a promising alternative capable of addressing many of these limitations. The process involves the application of a direct electrical current between sacrificial metal electrodes immersed in the wastewater. As the current flows, the anode undergoes controlled dissolution, releasing metal ions commonly aluminum (Al^{3+}) or iron (Fe^{2+}) into the solution (Kobya et al., 2020; Ghosh et al., 2008). These ions rapidly hydrolyze to form amorphous metal hydroxides, which act as coagulants. The in-situ generation of these coagulants eliminates the need for bulk chemical dosing, thereby reducing chemical handling and sludge management requirements (Bayar et al., 2011; Holt et al., 2005). Pollutant removal in EC occurs through multiple mechanisms: destabilization of colloidal particles, aggregation into larger flocs, flotation by hydrogen microbubbles generated at the cathode, and gravitational sedimentation (Emamjomeh and Sivakumar, 2009; Chen, 2004; Mollah et al., 2010). This multifaceted removal pathway enhances the treatment efficiency across a broad range of contaminants, including dyes, heavy metals, oils, and suspended solids (Barrera-Díaz et al., 2014; Heidmann and Calmano, 2010; Kobya et al., 2003).

A critical determinant of EC performance is the design and optimization of the electrode system. Electrode material dictates the nature and reactivity of the coagulants produced; for instance, aluminum electrodes are often preferred for color and turbidity removal, while iron electrodes show superior performance for phosphate and arsenic elimination (Vepsäläinen et al., 2012). Geometry, surface area, and inter-electrode spacing influence the electric field distribution, reaction kinetics, and mass transfer efficiency (Sahu et al., 2014; Sharma et al., 2019). Excessive spacing can lead to increased electrical resistance and energy consumption, whereas overly close spacing may hinder proper dispersion of coagulants and flocs. Additionally, optimized arrangements such as monopolar parallel, monopolar series, or bipolar configurations affect current pathways and operational stability (Akbal and Camcı, 2011; Linares-Hernández et al., 2009). Careful selection and configuration of electrodes enable enhanced pollutant removal rates while minimizing power requirements, making EC a competitive and sustainable choice for industrial wastewater treatment (García-Segura et al., 2017; Mechelhoff et al., 2013).

MATERIAL AND METHODS

The methodology flowchart (Fig. 1) outlines the sequential steps undertaken in the electrocoagulation (EC) experiment for treating industrial effluents (Bouaouine et al., 2015). The process begins with sample collection from selected industrial sources to ensure representation of diverse pollutant characteristics. The collected samples were preserved at 4 °C and analyzed within 24 h to maintain sample integrity. This was followed by the characterization of raw wastewater, including the determination of pH, chemical oxygen demand (COD) (Ziati et al., 2018), biochemical oxygen demand (BOD), turbidity, and metal concentrations. The reactor setup stage involved assembling a 5 L batch EC unit equipped with aluminum, iron, or hybrid electrodes. Electrode configurations (monopolar parallel or bipolar) and varying electrode spacings were then arranged to assess their influence on treatment performance. Operational parameters, including current density and treatment duration, were systematically adjusted, while all experiments were conducted under the natural pH conditions of the influent wastewater, without external pH modification. The wastewater subsequently underwent EC treatment, during which samples were collected at regular intervals for analysis. Finally, post-treatment testing was carried out using standardized APHA methods to evaluate pollutant removal efficiencies and to support optimization of the treatment process.

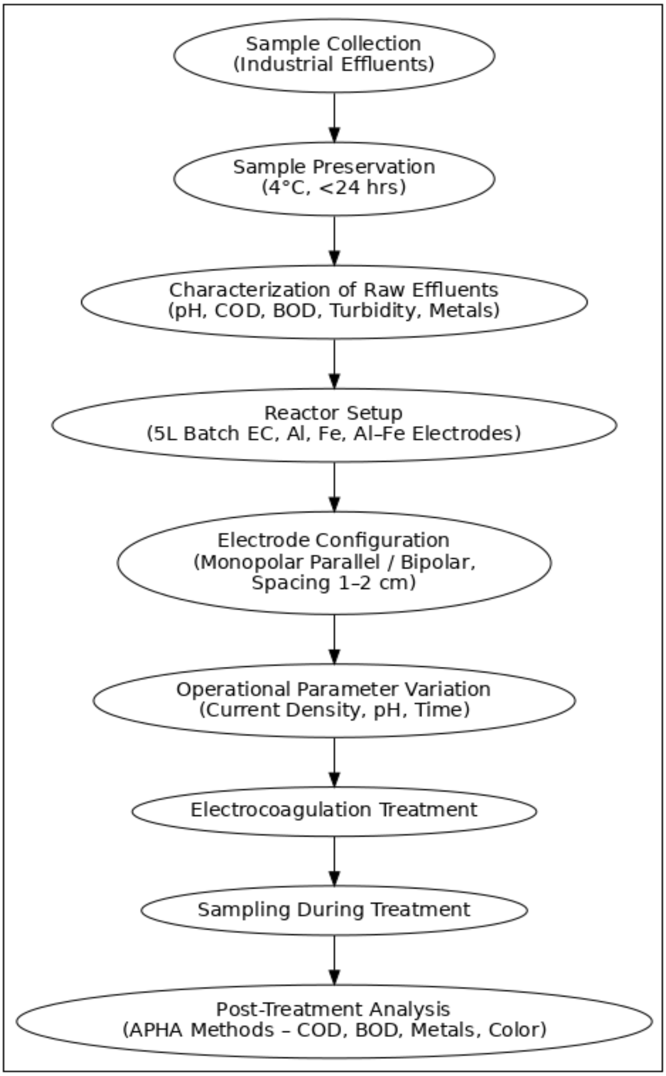

Figure 1: Methodology flowchart

Experimental apparatus

A 5-liter batch-type EC reactor was constructed for laboratory experiments (Fig. 2). The reactor body was made from transparent acrylic sheets for chemical resistance and visual observation. A modular electrode frame was designed to allow quick adjustment of electrode spacing and configurations.

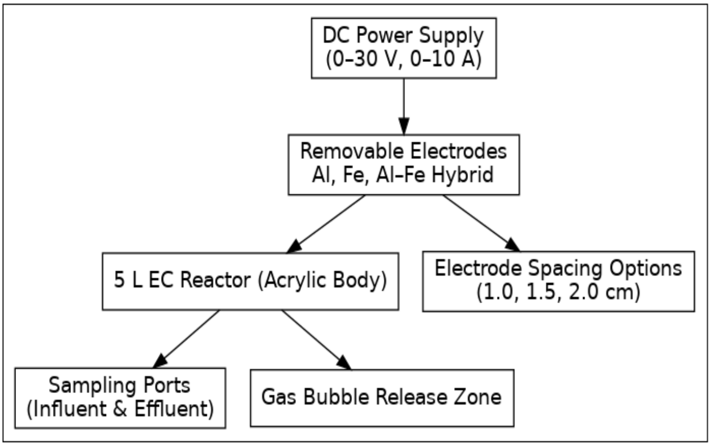

Figure 2: Schematic diagram of the EC reactor showing electrode configuration, sampling ports, and bubble release zones.

Three electrode types were tested:

1. high-purity aluminum (99.5%): to generate Al^{3+} ions for contaminant adsorption and color removal.
2. mild steel: to generate Fe^{2+}/Fe^{3+} ions for effective metal precipitation and phosphate removal.
3. hybrid alternating Al-Fe arrangement: to synergize the benefits of both metals in pollutant removal (Mollah et al., 2010).

The DC power supply (0-30 V, 0-10 A) enabled precise control of current density. Two electrode configurations were used:

1. monopolar-Parallel (MP-P): direct connection of all electrodes to the power supply, reducing voltage drop.
2. bipolar (BP): terminal electrodes connected to the power supply, intermediate electrodes polarized indirectly.

Electrode spacings of 1.0, 1.5, and 2.0 cm were tested based on prior optimization studies (Ghernaout and Elboughdiri, 2020).

Wastewater samples

Three industrial wastewater types were selected to represent diverse contamination profiles:

- textile effluent: high COD from dyes and surfactants, intense coloration, high turbidity.
- petroleum refinery effluent; oily wastewater containing emulsified hydrocarbons and grease.
- metal-finishing effluent: acidic pH, elevated heavy metals such as Pb^{2+} and Cr^{6+}.

Samples were collected in 20 L HDPE containers, stored at 4 °C, and analyzed within 24 hours following APHA guidelines (2022).

Analyses followed APHA Standard Methods (2022) (Table 1). The resulting data set presents a comparative snapshot of effluent quality from three representative industrial sectors textile processing, petroleum refining, and metal finishing each of which is known to generate wastewater with distinct chemical characteristics. The parameters reported in the table were selected to capture both general water quality conditions and sector-specific pollution signatures. Variations in pH values reflect the differing nature of industrial operations, ranging from alkaline discharges in textile processing to acidic effluents associated with metal finishing activities. Organic pollution levels, indicated by chemical oxygen demand (COD) and biochemical oxygen demand (BOD), highlight substantial differences in the strength and biodegradability of wastewater among the sectors, with textile and refinery effluents exhibiting considerably higher organic loads than metal finishing wastewater. Turbidity values further illustrate the relative presence of suspended and colloidal matter, which is most pronounced in textile processing effluents and progressively lower in refinery and metal finishing discharges. In addition, the occurrence of sector-specific heavy metals, such as lead in textile effluent and chromium in metal finishing wastewater, underscores the potential environmental and regulatory significance of trace contaminants beyond conventional organic indicators. Together, these results provide a clear basis for understanding inter-industry contrasts in wastewater composition and for evaluating the need for tailored treatment and management strategies across different industrial sectors.

Table 1: Physico-chemical characteristics of raw industrial wastewater.

Parameter	Textile Processing	Petroleum Refinery	Metal Finishing
pH	9.2	7.6	3.5
COD (mg/L)	2150	1850	920
BOD (mg/L)	870	620	120
Turbidity (NTU)	220	140	60
Key Metals (mg/L)	Pb: 0.6	-	Cr: 5.2

Analytical procedures

Analyses followed APHA Standard Methods (2022) (Table 1):

- COD: dichromate reflux method (5220 B).
- BOD: 5-day BOD test (5210 B).
- Turbidity: nephelometric method (2130 B).
- Heavy metals: atomic absorption spectroscopy (3111 B) after acid digestion.
- Color: spectrophotometric analysis at specific dye absorbance wavelengths.

All physicochemical and toxicological parameters were quantified using rigorously standardized analytical protocols in accordance with APHA Standard Methods (2022) (Table 1), ensuring methodological robustness and cross-sample comparability. Effluent pH was determined using calibrated electrometric techniques, revealing pronounced inter-industrial variability, with alkaline conditions dominating textile processing wastewater (pH = 9.2), near-neutral characteristics observed in petroleum refinery effluent (pH = 7.6), and strongly acidic conditions characterizing metal finishing discharge (pH = 3.5). These contrasts reflect process-specific chemical inputs and reaction environments.

Organic pollution loads were evaluated through the closed reflux dichromate method for chemical oxygen demand (COD; Method 5220 B) and the five-day biochemical oxygen demand assay (BOD_5; Method 5210 B). The markedly elevated COD and BOD concentrations in textile and refinery effluents indicate substantial organic and oxidizable pollutant burdens, whereas comparatively lower values in metal finishing wastewater suggest limited biodegradable organic content but potentially higher inorganic toxicity. Effluent clarity and particulate loading were assessed using the nephelometric turbidity method (Method 2130 B), with the highest turbidity recorded in textile effluents, consistent with the presence of suspended fibers, dyes, and auxiliary processing chemicals.

Trace metal concentrations were determined following acid digestion and subsequent analysis by atomic absorption spectroscopy (Method 3111 B), enabling sensitive detection of hazardous elements such as chromium in metal finishing wastewater and lead in textile effluent. In addition, color intensity in textile wastewater was quantified through spectrophotometric measurements at characteristic dye-specific absorbance wavelengths, providing an integrated assessment of residual chromophoric compounds. Collectively, the applied analytical framework offers a comprehensive and reliable basis for linking observed effluent characteristics to industrial process signatures and for informing targeted treatment and regulatory strategies.

The calculation of energy E is undertaken to provide a clear and quantifiable basis for understanding the physical or process-related effort required within the system under investigation. Rather than serving as an abstract mathematical exercise, the energy term represents the actual work input needed to drive the process, sustain operating conditions, or induce the observed transformation. By explicitly evaluating E, the analysis links theoretical relationships with measurable system performance, allowing the magnitude of resource consumption to be interpreted in practical terms.

Introducing the energy calculation at this stage is essential because it establishes a common reference point for comparing different operating scenarios, design alternatives, or treatment configurations. Without this step, subsequent results would lack context, making it difficult to assess whether observed efficiencies or losses are significant or merely incidental. The energy estimate also helps to identify dominant contributors to system demand, thereby clarifying where improvements, optimizations, or control measures may yield the greatest benefit.

In addition, calculating E supports transparent decision-making by translating complex interactions into a single, interpretable metric that can be related to cost, sustainability, or environmental impact. This approach ensures that the discussion remains coherent and logically structured, guiding the reader from the purpose of the analysis through to its implications, rather than presenting isolated statements or fragmented calculations.

Energy consumption was calculated using the following equation:

$$E = \frac{V I t}{1000 V} \quad (1)$$

Where: E = energy consumption (kWh/m^3), V = voltage (V), I = current (A), t = electrolysis time (h), V_r = reactor volume (m^3).

Process optimization

The following four process parameters were varied:

- - Current density: 10-150 A/m^2 (Kobya et al., 2019).
- - Electrode spacing: 1.0, 1.5, and 2.0 cm.
- - Initial pH: Adjusted using NaOH or H2SO4.
- - Electrolysis time: 10-60 minutes.

Data analysis and statistics

Experimental results were analyzed using one-way ANOVA to determine the significance of parameter effects on removal efficiencies ($p < 0.05$). Regression analysis was applied to fit removal data to first-order kinetic models, with R^2 values indicating goodness of fit. Energy efficiency and cost per cubic meter were also computed for each operating condition to identify the most cost-effective treatment setup (APHA, 2022; Kobya et al., 2019).

RESULTS AND DISCUSSION

Pollutant removal across configurations

The comparative performance evaluation revealed that hybrid Al-Fe electrode arrangements consistently outperformed single-metal configurations when treating mixed pollutant wastewater streams. The synergistic effect of aluminum's strong adsorption capacity and iron's superior precipitation ability enhanced contaminant removal. In textile wastewater, aluminum electrodes achieved the highest color removal (99%) (Fig. 3), while in metal-finishing effluents, hybrid electrodes removed 98.4% of Cr. Petroleum refinery effluents were treated most effectively using mild steel electrodes, given their affinity for hydrocarbon and oil emulsions.

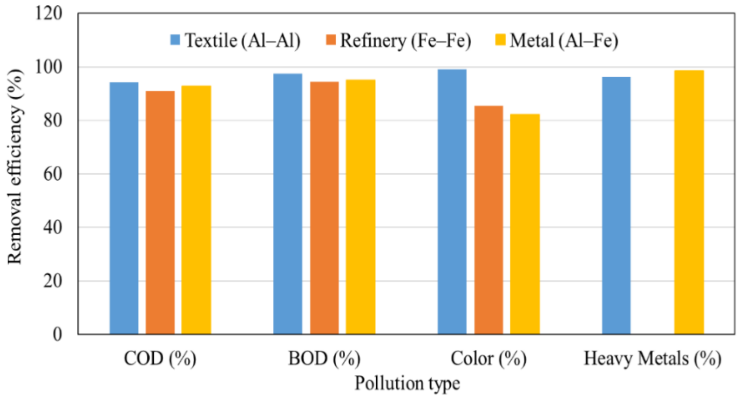

Figure 3: Comparative pollution removal efficiencies under optimal EC conditions.

Influence of electrode spacing

Electrode spacing played a critical role in determining removal efficiency and energy demand. At 1.0 cm, the shortest distance between plates, mass transfer was maximized, resulting in the highest removal efficiency (95%) (Table 2). However, energy consumption was slightly higher due to increased ohmic losses (Table 2). At 1.5 cm, removal efficiency remained almost identical (94.2%), but energy consumption dropped to 0.78 kWh/m³, representing the most cost-effective operational point. A spacing of 2.0 cm caused a noticeable reduction in removal efficiency due to reduced bubble-particle collision rates and weaker floc formation (Kobya et al., 2019).

Table 2: Effect of electrode spacing on EC performance.

Spacing	Removal Efficiency (%)	Energy (kWh/m³)
1.0 cm	95	0.82
1.5 cm	94.2	0.78
2.0 cm	91.4	0.72

Energy demand and operating economics

Energy consumption analysis demonstrated that optimal EC conditions can achieve > 90% COD removal with energy requirements under 0.8 kWh/m³. The hybrid Al-Fe configuration with 1.5 cm spacing emerged as the most practical choice, balancing high pollutant removal with minimal operational costs. This aligns with findings from Mollah et al. (2010), where hybrid setups provided enhanced treatment with reduced sludge management costs.

The performance comparison highlights the clear advantages of the hybrid aluminum–iron (Al-Fe) configuration over single-metal electrode setups. At a spacing of 1.5 cm, the hybrid arrangement achieved the highest chemical oxygen demand (COD) removal efficiency, reaching 92% (Table 3), which surpasses the 90% and 89% obtained with aluminum–aluminum (Al-Al) and iron–iron (Fe-Fe) electrodes, respectively. This superior removal efficiency can be attributed to the synergistic effect of aluminum and iron, which generates a broader range of coagulant species, enhancing the capture and destabilization of diverse pollutants.

In addition to improved treatment performance, the hybrid configuration demonstrated the lowest energy consumption at 0.78 kWh/m³, compared with 0.82 kWh/m³ for Al-Al and 0.86 kWh/m³ for Fe-Fe. This reduction in energy demand indicates that the hybrid setup not only delivers better contaminant removal but also operates more economically. The combined benefits of higher efficiency and lower operating cost position the hybrid Al-Fe configuration as the most practical and sustainable choice for industrial wastewater treatment.

Table 3: Performance comparison (Hybrid Al–Fe vs. single-metal configurations).

Configuration (spacing)	COD removal (%)	Energy consumption (kWh/m³)
Hybrid Al-Fe (1.5 cm)	92	0.78
Aluminum-Aluminum (1.5 cm)	90	0.82
Iron- Iron (1.5 cm)	89	0.86

Sludge yield and characteristics

One of the main advantages of EC over conventional coagulation methods was the reduction in sludge volume by 40-50%. The sludge generated had a higher dry density (~35%), making it easier to dewater and dispose of. The reduced moisture content also minimized transport and handling costs, addressing one of the major operational challenges of conventional coagulation (Ghernaout and Elboughdiri, 2020).

The comparison between electrocoagulation (EC) using hybrid aluminum-iron electrodes and conventional chemical coagulation shows a clear advantage for EC in sludge management. The sludge yield from EC was recorded at 0.8 g/L, which is significantly lower than the 1.5 g/L obtained from chemical coagulation (Fig. 4). This reduction in yield directly translates to decreased sludge handling, transportation, and disposal requirements, making EC more sustainable and cost-efficient. Additionally, the moisture content of EC-generated sludge was 65%, notably lower than the 75% observed in chemically coagulated sludge. Lower moisture content enhances dewatering efficiency, reduces drying time, and minimizes storage volume. These results indicate that EC not only reduces the total sludge volume but also produces sludge with improved physical properties, making post-treatment processing easier. The combined benefits of reduced quantity and better-quality sludge strengthen the case for adopting EC as an environmentally friendly and operationally efficient alternative to conventional coagulation methods for industrial wastewater treatment.

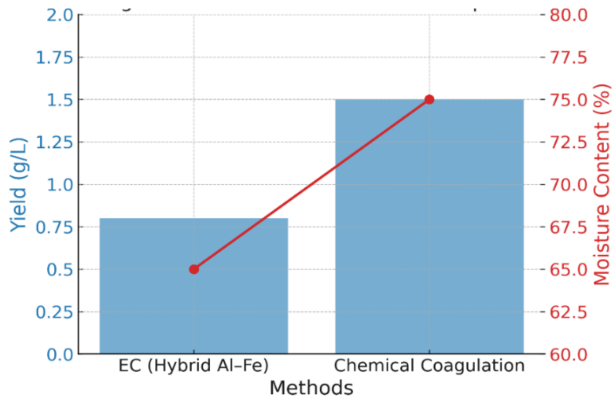

Figure 4: Sludge yield and moisture content comparison

Treatment kinetics

Treatment kinetics showed rapid removal of contaminants during the first 15–20 minutes of electrolysis, after which removal curves plateaued. This initial rapid removal was attributed to high coagulant generation rates and active floc formation, while the plateau phase resulted from reduced pollutant availability and partial electrode passivation.

The COD removal curve (Fig. 5) demonstrates a rapid decline in organic pollutant concentration during the initial treatment phase. Within the first 15 minutes of electrocoagulation, removal efficiency reached approximately 90%, indicating highly effective contaminant destabilization and floc formation during this early stage. Beyond 20 minutes, the curve began to level off, suggesting that most readily removable organic matter had been extracted and that residual COD was primarily composed of more stable compounds. The plateau also reflects a gradual reduction in active coagulant generation due to partial electrode passivation. This trend highlights that the majority of COD removal occurs in the early operational period, which offers opportunities for optimizing treatment time and reducing energy consumption without compromising water quality. Such kinetics confirm the suitability of electrocoagulation for fast, high-efficiency treatment of industrial effluents, particularly when using optimized hybrid aluminum–iron electrode configurations under controlled operating conditions.

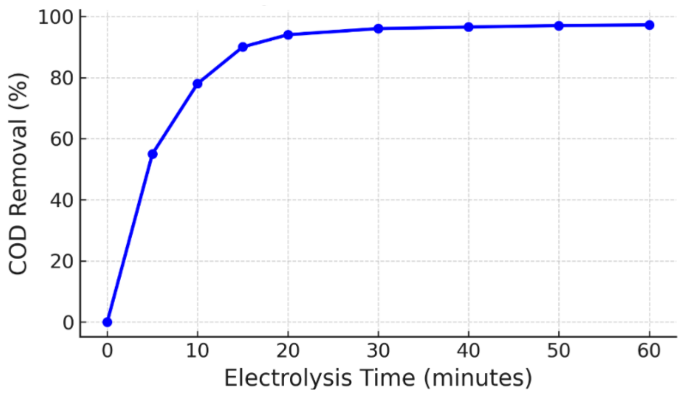

Figure 5: **COD removal vs. time for textile wastewater using hybrid Al-Fe electrodes**

Technology comparison

When compared to chemical coagulation and membrane-based treatment systems, EC demonstrated broader contaminant removal capability, lower sludge production, and better adaptability for automation (Table 3). Although EC's operating cost was slightly higher than chemical coagulation, its lower sludge disposal costs and versatility made it competitive.

The comparison highlights that electrocoagulation (EC) offers a clear advantage in terms of chemical usage, producing low sludge volumes and effectively handling a broad range of contaminants. Unlike chemical coagulation, which requires large quantities of coagulants and generates significant sludge, EC minimizes both chemical consumption and waste generation, reducing disposal challenges. Membrane systems also use minimal chemicals but are prone to severe fouling and scaling, leading to higher maintenance demands. In terms of operating cost, EC falls within the medium range, slightly higher than chemical coagulation due to electricity requirements, but still more economical than membrane-based methods (Table 4). The sludge volume from EC is considerably lower than that from chemical coagulation and easier to manage. Furthermore, while membrane systems and EC both address a broad spectrum of contaminants, membranes incur higher capital and operational expenses. Overall, EC provides a balanced approach, combining versatility and waste reduction with reasonable operating costs, making it a competitive choice for industrial wastewater treatment.

Table 4: Comparative performance of EC and conventional treatment methods

Feature	EC	Chemical Coagulation	Membrane Systems
Chemical use	Low	High	Low
Sludge volume	Low	High	Medium
Operating cost	Medium	Low-Medium	High
Fouling/scaling	Medium	Low	High
Contaminant range	Broad	Moderate	Broad

comparison with existing literature

Traditional EC systems with symmetrical electrodes typically report TOC removal efficiencies ranging from 37% to 80% under similar operating conditions. While hybrid approaches such as EC combined with electrooxidation or advanced oxidation have demonstrated higher removal efficiencies, they often incur higher operational costs, increased sludge generation, and greater system complexity. In contrast, the DEP-based configuration reported here consistently outperformed conventional EC systems, achieving removal efficiencies at the upper limit of reported literature while simultaneously reducing material consumption. Moreover, the reduced electrode corrosion directly addresses one of the most cited limitations in EC applications, offering a practical improvement over the methods currently documented.

significance and practical implications

The integration of DEP-inducing electrodes represents a notable step forward in advancing EC technology, bridging the gap between laboratory innovation and industrial feasibility. By combining superior pollutant removal with lower energy demand, reduced electrode consumption, and simulation-backed optimization of current and distance, this study provides a scalable and predictive framework for future system design. Compared to state-of-the-art techniques, the proposed configuration achieves a rare balance of high efficiency, operational simplicity, and cost-effectiveness, making it an impactful contribution to wastewater treatment research. Importantly, the approach aligns with global sustainability objectives by minimizing waste generation and reducing operational footprints, thereby strengthening its potential for widespread adoption in industrial and municipal wastewater treatment plants.

CONCLUSION

The present investigation confirms that electrocoagulation (EC) is a robust and versatile approach for addressing the treatment challenges posed by complex industrial effluents. Through systematic experimentation with textile, petroleum refinery, and metal-finishing wastewaters, it was demonstrated that careful optimization of electrode material, arrangement, and spacing can significantly enhance removal efficiency while maintaining economic feasibility. Across all studied effluent types, optimized configurations achieved substantial reductions in contamination levels. Chemical oxygen demand consistently decreased by more than 90%, biological oxygen demand showed reductions above 94%, and targeted heavy metals were eliminated at efficiencies exceeding 95%. Hybrid aluminum–iron electrode assemblies emerged as the most effective configuration, leveraging the combined coagulant properties of both materials to address a wide pollutant spectrum. This arrangement not only improved contaminant removal but also minimized power consumption, with energy requirements dropping to below 0.8 kWh/m^3 in optimal setups.

Electrode spacing was identified as a critical performance determinant, with a gap of 1.0-1.5 cm providing the best balance between high removal rates and reasonable energy expenditure, whereas wider spacing led to measurable reductions in treatment efficiency. Compared to conventional chemical coagulation, EC generated significantly less sludge, reduced by approximately 40-50%, and yielded solids that were denser and easier to dewater, thereby lowering post-treatment handling requirements. The findings highlight EC's capability to address diverse wastewater streams without the continuous addition of external chemicals, making it an environmentally aligned and operationally straightforward solution. Furthermore, the process offers flexibility in scale-up, potential for automation, and integration into hybrid treatment systems. Given its demonstrated performance, resource efficiency, and reduced secondary pollution, EC with optimized electrode configurations stands as a technically and economically promising technology for sustainable industrial wastewater management. Continued research into scale-up strategies, electrode durability, and sludge valorization will further strengthen its role in future water treatment infrastructures.

Novelty of the work

The present study introduces an innovative electrocoagulation (EC) system based on an asymmetrical aluminum electrode configuration designed to induce dielectrophoretic (DEP) forces. Unlike conventional symmetrical setups, this configuration optimizes pollutant capture through enhanced particle migration and aggregation dynamics. Under optimal conditions 600 mA applied current, 0.5 cm interelectrode distance, and 30 minutes of electrolysis, the system achieved 87.7% total organic carbon (TOC) removal, along with significant reductions in suspended solids (20 mg/L) and turbidity (14 NTU). In addition, energy consumption remained relatively low at 3.92 kWh/m³, while electrode wear was reduced by 27.3%, underscoring both environmental and economic advantages.

Future scope and limitations

Electrocoagulation (EC) demonstrates considerable potential for industrial wastewater treatment due to its operational simplicity and effectiveness across a wide range of pollutants. Future research should focus on scaling EC systems to industrial applications, supported by pilot-scale studies to evaluate long-term performance under variable effluent loads. Further improvements in electrode materials, including enhanced durability and self-cleaning features, may help mitigate fouling and passivation, thereby improving process reliability. In addition, integrating EC with complementary treatment technologies, such as membrane filtration or advanced oxidation processes, could enhance the removal of complex or recalcitrant contaminants.

Despite these prospects, several limitations and uncertainties must be acknowledged. Energy consumption and electrode replacement contribute to operational costs and may limit applicability in resource-constrained settings. Variations in wastewater composition can affect treatment efficiency and introduce uncertainty in process performance, highlighting the need for careful operational control. Furthermore, the treatment of high-strength or highly saline effluents may require process modification to maintain effectiveness. Addressing these technical and economic challenges through continued research and optimization is essential for the broader adoption of EC in industrial wastewater management.

Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could influence the work reported in this article.

Acknowledgement

The authors would like to thank the Indian National Institute of Technology, Raipur, for their kind support and for providing the opportunity to conduct the present study.

REFERENCES

ACHOUR S., GUERGAZI S., GUESBAYA N., SEGHAIRI N., YOUCEF L., (2002). Impact of chlorination, flocculation, and adsorption processes on the evolution of organic and mineral compounds in natural water, Larhyss Journal, No 1, pp. 107-128. (In French)

ACHOUR S., CHABBI F. (2017). study of oxidation/disinfection steps of treatment plant of Ain Tinn (Mila, eastern Algeria), Larhyss Journal, No 31, pp. 233(247. (In French)

ACHOUR S., TIBERMACINE A.A., CHABBI F. (2017). Iron and Manganese in natural waters and chemical oxidation methods. case of Algerian waters, Larhyss Journal, No 32, pp. 139-154. (In French)

AHMAD A. L., OOI B. S., LOW S. C., ISMAIL A. (2020). Fouling control in membrane filtration for water treatment, *Separation and Purification Reviews*, Vol. 49, Issue 4, pp. 290-330.

AKBAL F., CAMCI S. (2011). Copper, chromium and nickel removal from metal plating wastewater by electrocoagulation, *Desalination*, Vol. 269, Issues 1-3, pp. 214-222.

APHA. (2022). *Standard methods for the examination of water and wastewater,* 23rd Edition, American Public Health Association, Washington, D.C. (Accessed date: November 27, 2017)

BARRERA-DÍAZ C., FRONTANA-URIBE B.A., BILYEU B. (2014). Electrocoagulation: Fundamentals and applications in water treatment, *Electrochimica Acta*, Vol. 132, Issue 3, pp. 437-451.

BAYAR S., YILDIZ Y. Ş., YILMAZ A. E., IRDEMEZ Ş. (2011). The effect of stirring speed and current density on removal efficiency of poultry slaughterhouse wastewater by electrocoagulation method, *Desalination*, Vol. 280, Issues 1-3, pp. 103-107.

BOUAOUINE O., KHALIL F., CHTIOUI H., ZAITAN H., HARRACH A. (2015). Electrocoagulation treatment of leachate from the controlled public landfill of the city of Fes (Morocco), Larhyss Journal, No 23, pp. 53-67. (In French)

CHADEE A., RATHORE K., CHOUDHARY L., VERMA S., MEHTA D. (2024). The korba coal mining zone in India assessment of risk health and pollutant sources, Larhyss Journal, No 60, pp. 113-131.

CHEN G. (2004). Electrochemical technologies in wastewater treatment, *Separation and Purification Technology*, Vol. 38, Issue 1, pp. 11-41.

CHOKSI K.N., SHETH M.A., MEHTA D. (2015a). To assess the performance of Sewage Treatment Plant: A Case study of Surat city. International Journal of Engineering and Technology (IRJET), Vol. 2, Issue 8, pp. 1071-1075.

CHOKSI K.N., SHETH M.A., MEHTA D. (2015b). To evaluate the performance of Sewage Treatment Plant: A Case study, International Research Journal of Engineering and Technology (IRJET), Vol. 2, Issue 8, pp. 1076-1080.

EMAMJOMEH M.M., SIVAKUMAR M. (2009). Review of pollutants removed by electrocoagulation and electrocoagulation/flotation processes, *Journal of Environmental Management*, Vol. 90, Issue 5, pp. 1663-1679.

GARCÍA-SEGURA S., EIBAND M.M., DE MELO J.V., MARTÍNEZ-HUITLE C.A. (2017). Electrocoagulation and advanced electrochemical oxidation processes: A review on the fundamentals and applications, *Journal of Electroanalytical Chemistry*, Vol. 801, Issue 2, pp. 267-299.

GHECHAM F.Z., GUERGAZI S., ACHOUR S. (2018). Removal of caffeine by coagulation-flocculation with aluminum sulfate and effect of metal salts, Larhyss Journal, No 34, pp. 115-126. (In French)

GHERNOUT D., ELBOUGHDIRI N. (2020). Electro membrane processes and electrocoagulation for wastewater reuse: A review, *Applied Water Science*, Vol. 10, Issue 2, pp. 1-20.

GHOMRI F., LAHSINI A., LAAJEB A., ADDAOU A. (2013). The removal of heavy metal ions (copper, zinc, nickel and cobalt) by natural bentonite, Larhyss Journal, No 12, pp. 37-54.

GHOSH D., MEDHI C. R., PURKAIT M. K. (2008). Treatment of fluoride-containing drinking water by electrocoagulation using monopolar and bipolar electrode connections, *Chemosphere*, Vol. 73, Issue 9, pp. 1393-1400.

GUERGAZI S., AMIMEUR D., ACHOUR S. (2013). Elimination of humic substances of two Algerian surface waters by adsorption on activated carbon and bentonite, Larhyss Journal, No 13, pp. 125-137. (In French)

HEIDMANN I., CALMANO W. (2010). Removal of Zn (II), Cu (II), Ni (II), Ag(I), and Cr (VI) in aqueous solutions by aluminum electrocoagulation, *Journal of Hazardous Materials*, Vol. 152, Issue 3, pp. 934-941.

HOLT P.K., BARTON G.W., MITCHELL C.A. (2005). The future for electrocoagulation as a localized water treatment technology, *Chemosphere*, Vol. 59, Issue 3, pp. 355-367.

KHELIEL O., OUAKOUAK A.E.K., YOUCEF L., ACHOUR S. (2015). Groundwater denitrification by adsorption on activated carbon and by coagulation-flocculation with aluminum sulfate, Larhyss Journal, No 21, pp. 191-200. (In French)

KOBYA M., DEMIRBAS E., BAYRAMOGLU M., SENSOY M. T. (2003). Treatment of textile wastewater by electrocoagulation using iron and aluminum electrodes, *Journal of Hazardous Materials*, Vol. 100, Issues 1-3, pp. 163-178.

KOBYA M., HIZ H., SENTURK E., AYDINER C., DEMIRBAS E. (2019). Treatment of potato chips manufacturing wastewater by electrocoagulation, *Desalination*, Vol. 190, Issues 1-3, pp. 201-211.

KOBYA M., YILDIZ Y. Ş., DELIPINAR S., DEMIRBAS E. (2020). A review on electrocoagulation for the treatment of industrial wastewaters: Mechanisms, influencing parameters, and performance evaluation, *Desalination and Water Treatment*, Vol. 199, Issues 1-3, pp. 1-24.

KUMAR P., PAL P. (2021). Comparative assessment of electrocoagulation vis-à-vis conventional techniques for treatment of industrial effluents, *Journal of Environmental Chemical Engineering*, Vol. 9, Issue 2, Paper ID 104709.

LINARES-HERNÁNDEZ I., BARRERA-DÍAZ C., ROA-MORALES G., BILYEU B., UREÑA-NÚÑEZ F. (2009). Influence of the anodic material on electrocoagulation performance, *Chemical Engineering Journal*, Vol. 148, Issue 1, pp. 97-105.

MASMOUDI T., GUERGAZI S., ACHOUR S. (2018). Mercury removal by activated carbon, Larhyss Journal, No 34, pp. 21-38. (In French)

MECHELHOFF M., STOLLE S., BEHRENS H., WORCH E. (2013). Optimized electrode arrangements for efficient electrocoagulation, *Water Research*, Vol. 47, Issue 15, pp. 5439-5446.

MOLLAH M.Y. A., GOMES J. A. G., DAS K. K., COCKE D. L. (2010). Electrochemical treatment of pollutants in aqueous media: An overview, *Journal of Hazardous Materials*, Vol. 174, No 1-3, pp. 463-492.

MOLLAH M.Y.A., SCHENNACH R., PARGA J.R., COCKE D. L. (2004). Electrocoagulation (EC) - Science and Applications, *Journal of Hazardous Materials*, Vol. 84, No 1, pp. 29-41.

MORADI S., RAEISI N., MEHTA D., ESLAMIAN S. (2025). Investigation of the effect of water treatment plant effluent on river quality: a case study, International Journal of Environment and Waste Management, Vol. 36, Issue 4, pp. 438-451.

OTURAN M.A., AARON J.J. (2014). Advanced oxidation processes in water/wastewater treatment: Principles and applications, *Critical Reviews in Environmental Science and Technology*, Vol. 44, Issue 23, pp. 2577-2641.

PANDEY A., VERMA S., MEHTA D., RHOWENA J., AZAMATHULLA H. (2025). A New Portable Water Filter System for Wastewater, Larhyss Journal, No 61, pp. 169-187.

PATEL R.K., SHANKAR R., KHARE P., MONDAL P. (2022). Ultrasonication coupled electrochemical treatment of sugar industry wastewater: optimization, and economic evaluation, Korean Journal of Chemical Engineering, Vol. 39, Issue 7, pp. 1821-1830.

SAHU O.P., MAZUMDAR B., CHAUDHARI P.K. (2014). Treatment of wastewater by electrocoagulation: A review, *Environmental Science and Pollution Research*, Vol. 21, Issue 4, pp. 2397-2413.

SBAI G., LOUKLI M. (2015). Electrochemical treatment of margins and identification of compounds before and after treatment by gas chromatography coupled with mass spectroscopy, Larhyss Journal, No 22, pp. 139-152. (In French)

SHARMA S., SIMSEK H., AGRAWAL S. (2019). Electrocoagulation treatment of wastewater: Recent trends and future directions, *Environmental Science: Water Research & Technology*, Vol. 5, Issue 4, pp. 623-642.

SIVAKUMAR, M., RAMEZANIANPOUR, M., O'HALLORAN, G. (2015). Brackish water treatment for reuse using vacuum membrane distillation process, Water Science and Technology: Water Supply, Vol. 15, Issue 2, pp. 362-369.

TELLEZ M., WOLFF M. S. (2016). The public health reach of high fluoride vehicles: Examples of innovative approaches, *Caries Research*, Vol. 50, Issue 1, pp. 61-67. https://doi.org/10.1159/000443186

TOLKOU A.K., MANOUSI N., ZACHARIADIS G.A., KATSOYIANNIS I.A., DELIYANNI E.A. (2021). Recently developed adsorbing materials for fluoride removal from water and fluoride analytical determination techniques: A review, *Sustainability*, Vol. 13, Issue 13, Paper ID 7061.

UNDE M.P., PATIL R.U., DASTOOR P.P. (2018). The untold story of fluoridation: Revisiting the changing perspectives, *Indian Journal of Occupational and Environmental Medicine*, Vol. 22, Issue 3, pp. 121-126.

VEPSÄLÄINEN M., SELIN J., RANTALA R., PULLIAINEN M. (2012). Investigation of the effect of electrode material on electrocoagulation efficiency for the removal of phosphate from water, *Separation and Purification Technology*, Vol. 93, Issue 2, pp. 1-6.

VERMA A.K., DASH R.R., BHUNIA P. (2019). A review on chemical coagulation/flocculation technologies for removal of colour from textile wastewaters, *Journal of Environmental Management*, Vol. 93, Issue 1, pp. 154-168.

VERMA D., SUPE J., VERMA S., SINGH R.R. (2024). Removal of fluoride from drinking water by utilizing modified bagasse sugarcane as low-cost adsorbents for Bilaspur City, Chhattisgarh, *Journal of Environmental Informatics Letters*, Vol. 11, Issue 2, pp. 69-81.

WAGHMARE S.S., ARFIN T. (2015). Fluoride removal from water by various techniques, *International Journal of Innovative Science, Engineering & Technology*, Vol. 2, Issue 3, pp. 560-571.

YADAV S., KHAN F., RATHORE K., VERMA S., MEHTA D. (2024). Household waste water treatment with the aid of activated charcoal, Larhyss Journal, No 60, pp. 133-150.

YING SHI C., HUI TING L. L., BOON SENG O. (2020). Membrane distillation for water recovery and its fouling phenomena, *Journal of Membrane Science and Research*, Vol. 6, Issue 1, pp. 107-124.

ZIATI M, CHERIFI O., YAHIA Z. (2018). Removal of chemical oxygen demand from tannery wastewater by Fenton's reagent, Larhyss Journal, No 33, pp. 111-121.