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Treatment of Contaminated Water from the Oil Industry Using Electrocoagulation with Aluminum Electrodes

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Treatment of Contaminated Water from the Oil Industry Using Electrocoagulation: A Bibliometric Analysis

ABSTRACT

This review article presents a bibliometric analysis aimed at examining recent advances in the treatment of contaminated water from the oil industry using electrocoagulation (EC), evaluating the operational parameters that influence removal efficiency. A bibliometric analysis and a systematic review were conducted on 80 experimental articles (2021–2026) retrieved from Scopus. VOSviewer (threshold of 4 occurrences) was used to identify thematic clusters, and inclusion criteria based on thematic affinity, technology evaluated, and experimental nature were applied. Four clusters were identified: electrocoagulation, coagulation, and turbidity (39 items); COD, current density, and energy consumption (21); electrodes, water treatment, and contaminants (21); and oily water, petroleum, and demulsification (7). Efficiencies range from 90–99% for oils, 82–99.6% for COD, 95–100% for TSS, and 96–99% for turbidity, with current densities of 1–30 mA/cm² and a pH of 6–9. EC is a versatile and sustainable technology for contaminated water from the oil industry, with efficiencies exceeding 90%. Parameter optimization and the integration of hybrid technologies improve efficiency and reduce energy costs. The main gaps are industrial-scale upscaling, electrode stability, and cost optimization.

Keywords: Electrocoagulation, contaminated water, oil industry, removal parameters

1 INTRODUCTION

Freshwater scarcity and the degradation of water resources are among the most critical environmental challenges of the 21st century, exacerbated by population growth, industrialization, and climate change (Vieira et al., 2025). The oil industry contributes significantly to this problem, as it generates large volumes of contaminated water including produced water, refinery effluents, drilling water, and drilling mud that contain emulsified oils, aromatic hydrocarbons, heavy metals,

and dissolved salts (Moussavi et al., 2021), which poses a severe environmental risk if discharged without proper treatment (Jiang et al., 2026). Conventional treatment methods, such as chemical coagulation and flotation, have limitations related to high reagent consumption, the generation of secondary sludge, and low efficiency in removing stable emulsions (Zhang et al., 2024).

In this context, electrocoagulation (EC) has emerged as a promising technology for the remediation of contaminated water from the oil industry (Yang et al., 2026). This electrochemical process generates coagulants in situ (Al^{3+} , Fe^{2+}) by applying an electric current to submerged electrodes, destabilizing oil-in-water emulsions and enabling the simultaneous removal of oils, COD, turbidity, and heavy metals (Behera et al., 2025; Madhavan & Antony, 2021). Compared to traditional chemical coagulation, ED reduces the volume of sludge generated, eliminates the need for chemical inputs, and allows for integration with renewable energy sources, positioning it as a sustainable and cost-effective alternative (Nahla et al., 2026). Despite growing scientific interest, research on EC applied to contaminated water from the oil industry has significant gaps: the dispersion of experimental results, the lack of consensus on optimal operating parameters—current density, pH, electrolysis time, and electrode configuration—and the limited integration of hybrid technologies (Mukherjee et al., 2026). These gaps hinder the comparison of efficiencies and the transfer of knowledge to full-scale industrial applications (Moneer et al., 2023). Bibliometric analysis allows for the identification of emerging trends, thematic clusters, and critical parameters that shape research in this field. Recent studies have shown that optimizing current density, pH, and electrode configuration can increase removal efficiency to over 90%, while simultaneously reducing energy consumption (Wang et al., 2022).

Furthermore, the integration of hybrid technologies has made it possible to achieve 100% removal efficiencies for COD and turbidity, meeting standards for agricultural reuse (Moneer et al., 2023). The objective of this review article is to comprehensively analyze recent advances in the treatment of contaminated water

from the oil industry using electrocoagulation, highlighting technological and methodological innovations in this field.

2 MATERIALS AND METHODOLOGY

2.1 Data Sources and Selection Criteria

The literature review was conducted on the Scopus® - Elsevier BV platform, recognized as one of the most comprehensive and rigorous databases in the scientific field (Miyahira, 2024; Page et al., 2021), which helps minimize the biases inherent in literature searches (Saldaña & Piña, 2025). The search was conducted on September 1, 2026, using the following algorithm:

TITLE-ABS-KEY(electrocoagulation OR "electro-coagulation") AND
TITLE-ABS-KEY(petroleum OR oil OR hydrocarbon* OR "oily wastewater" OR
"oil-water emulsion" OR "oilfield wastewater" OR "produced water" OR "refinery
wastewater" OR "petroleum wastewater" OR "oil-contaminated water") AND
TITLE-ABS-KEY(water OR wastewater OR effluent* OR emulsion*) AND
PUBYEAR > 2020 AND PUBYEAR < 2027

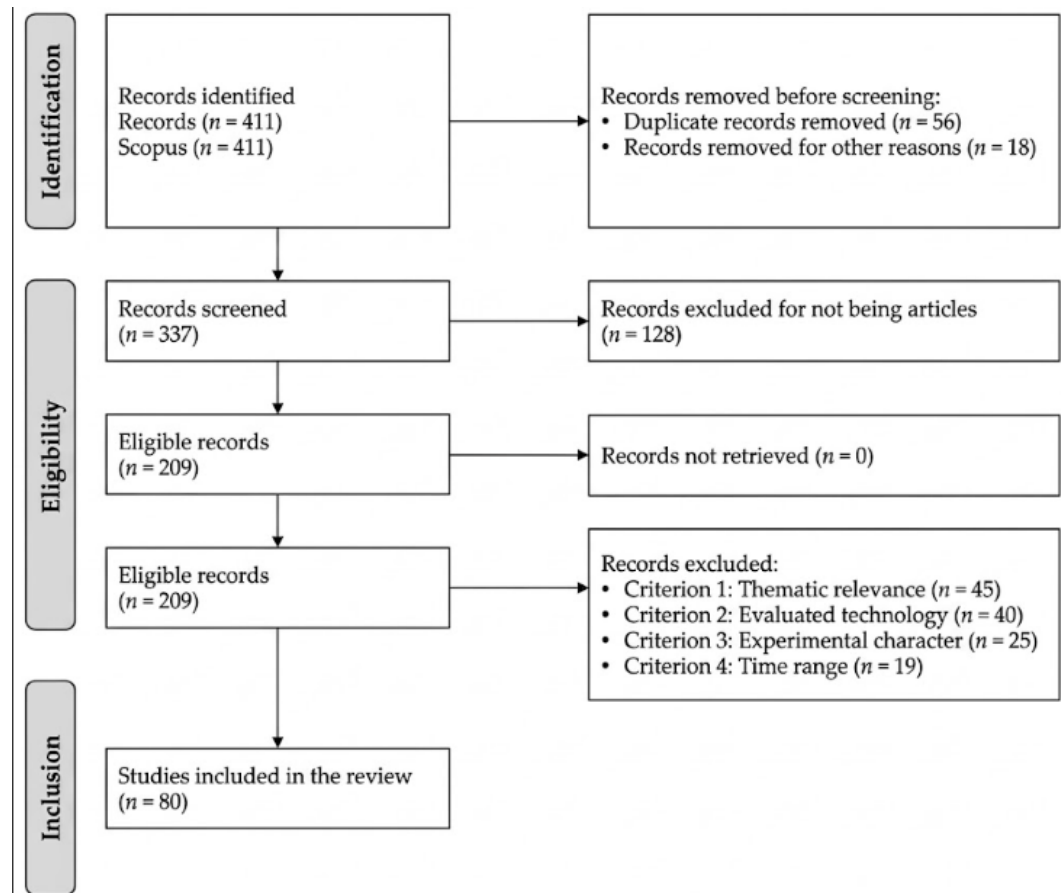
In addition, advanced search codes were implemented to consolidate the DOI identifiers of the preselected manuscripts, streamlining document retrieval and eliminating the need for individual searches. The initial search yielded 411 records, to which the following inclusion criteria were applied:

- a) Thematic relevance: studies related to the oil industry (produced water, refinery effluents, drilling water, drilling mud)
- b) Technology evaluated: research focused on electrocoagulation as the primary or combined process.
- c) Experimental nature: studies providing empirical data on electrocoagulation (theoretical reviews without original evidence were excluded).
- d) Time frame: publications from 2021 to 2026, to ensure the findings remain current.

After applying these filters, a database of 80 articles was compiled for analysis (Figure 1). The data were exported in CSV format, containing the complete information and cited references.

Figure 1

PRISMA Flowchart



2.2 Bibliometric Analysis

The VOSviewer software (Version 1.6.18) was used for the bibliometric analysis. To construct the map, a threshold of at least 4 occurrences was established for the inclusion of keywords. Of a total of 825 terms initially identified, 88 met this criterion after applying the co-occurrence normalization method and were organized into 4 clusters (Table 1). Since terminology retains its semantic precision in the original language of

publication, the maps presented in Figures 1 and 2 were generated in English.

Table 1

Clusters by color and by number of elements, obtained using the VosView software

Cluster	Color	Elements	Keywords
1	Red	39	Electrocoagulation, coagulation, turbidity
2	Green	21	Chemical oxygen demand, current density, energy consumption
3	Blue	21	Electrodes, water treatment, pollutants
4	Yellow	7	Oily water, petroleum, demulsification

Table 1 presents the distribution of the clusters generated from the keywords associated with the 80 articles selected from the Scopus database for the period 2021–2026. These thematic categories were essential for guiding the collection of information and structuring the bibliometric analysis of the review.

3 RESULTS AND DISCUSSION

3.1 Bibliometric Analysis by Keywords

Figure 2

Cluster map for 80 scientific articles, analyzed with VOSviewer using the normalized association method

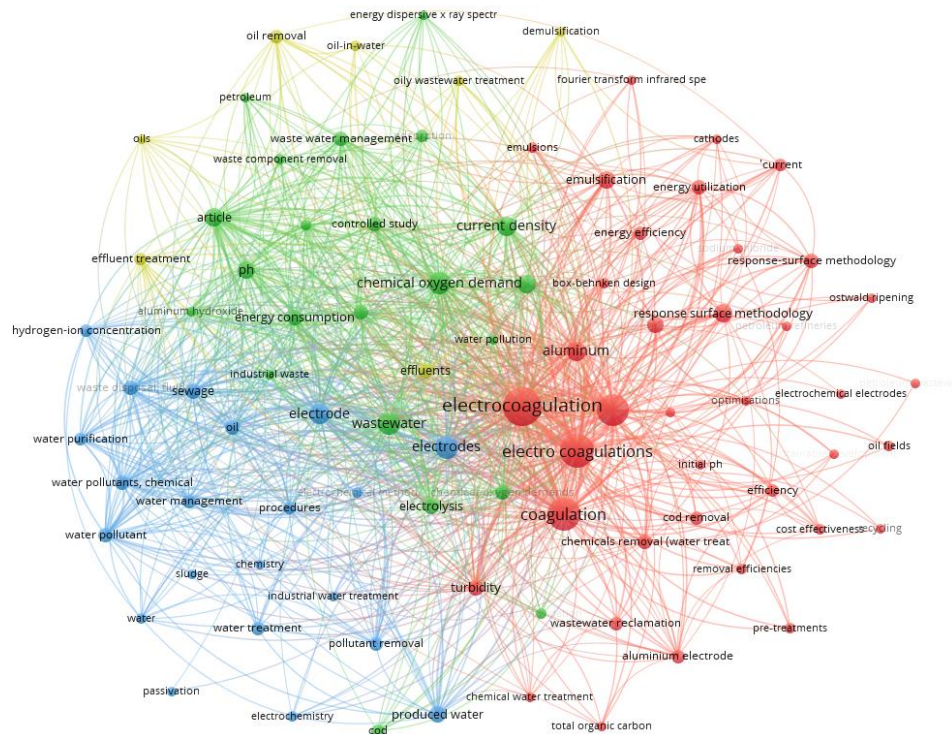


Figure 2 shows the association-based co-occurrence map of 80 articles, revealing four clusters. The red cluster (39 items) groups together electrocoagulation, coagulation, and turbidity, linking the process to its mechanism and outcome. The green cluster (21 elements) relates chemical oxygen demand to current density and energy consumption, highlighting the functional relationship between pollutant, parameter, and cost. The blue cluster (21 elements) addresses electrodes, water treatment, and pollutants, highlighting the instrumental component of the process. The yellow cluster (7 elements) focuses on oily water, petroleum, and demulsification, representing the specific thematic core of oil remediation.

Map of keyword clusters over time (years)

A horizontal timeline bar with a color gradient from dark blue to yellow. It has tick marks and labels for 2023.0, 2023.2, 2023.4, 2023.6, 2023.8, and 2024.0.

3.2.1 Cluster 1 (Electrocoagulation, Coagulation, Turbidity)

This cluster brings together studies that address the process (electrocoagulation), the mechanism (coagulation), and the outcome (turbidity). Electrocoagulation generates coagulants in situ (Al^{3+} , Fe^{2+}) which destabilize oil-water emulsions; coagulation agglomerates contaminants; and turbidity is the

indicator that reflects the efficiency of colloidal particle and oil droplet removal (Awaad et al., 2026).

It was noted that EC generates less sludge and does not require the addition of chemicals, unlike traditional chemical coagulation (Shokri & Sanavi, 2022). It was demonstrated that a spiral electrode configuration reduces energy consumption by ~20% and achieves 97% turbidity removal at 500 rpm (Jafari et al., 2023). A 99% turbidity removal rate and oil levels <60 mg/L were achieved using an aerated EC-flotation reactor (Choun et al., 2023). Simultaneous removal of 85% of oil and 80% of ammonia was achieved, with electrical conductivity identified as a determining factor (Awaad et al., 2026). It was demonstrated that perforated iron electrodes achieve outstanding turbidity removal at neutral pH, at a cost of \$2.39/m³ (Sevim et al., 2024). A 99% oil separation efficiency was achieved using aluminum electrodes coated with chitosan hydrogel (Bairagi et al., 2024). An 86% oil removal rate was achieved using curved electrodes with a tangential inlet (Domênico et al., 2022). An $91 \pm 4\%$ oil removal rate and a $97 \pm 2\%$ turbidity removal rate were achieved using aluminum mesh electrodes (Thomes et al., 2025). An oil removal rate of 98.38% was achieved using perforated electrodes (Yang et al., 2026). A COD removal rate of 90.86% was reported using aluminum and stainless steel mesh electrodes (Wang et al., 2022). A reduction in COD from 620 to 18.0 mg/L, TOC to 7.60 mg/L, and turbidity to 0.350 NTU was reported using the electrocoagulation + ultrafiltration process (Vien et al., 2026). A 94% reduction in turbidity and $\geq 90\%$ reduction in COD were achieved with EC (Moussavi et al., 2021). A 97.3% reduction in turbidity and a 73.4% reduction in conductivity were achieved with EC in a bipolar system (Moneer et al., 2023).

3.2.2 Cluster 2 (Chemical Oxygen Demand, Current Density, Energy Consumption)

This cluster groups together studies that address the pollutant (COD), the operating parameter (current density), and the cost (energy consumption). The relationship is functional: COD is the primary indicator of organic pollution; its removal depends directly on the applied current density; and this, in turn,

determines energy consumption, which is the main operating cost of the treatment. Higher current density results in greater COD removal, but also higher energy consumption. The integration of electrocoagulation, ultrafiltration, and reverse osmosis (EC-UF-RO) achieves COD removal of 84.66% with EC alone and ~100% with EC-UF-RO, with a total specific energy consumption (SEC) of ~4.52 kWh/m³ for EC-UF-BWRO (reverse osmosis for brackish water) and ~7.23 kWh/m³ for EC-UF-SWRO (reverse osmosis for seawater) (Mukherjee et al., 2026). A 93.53% COD removal rate was reported at 0.160 kWh/kg COD using recycled anodes, demonstrating that current density is the factor that simultaneously controls both removal efficiency and cost (Song et al., 2022). A 90.2% COD removal rate was achieved using only 1.28 kWh/kg COD via a basalt cathode with carbon nanotubes and silver nanowires powered by solar energy, demonstrating that current density can be optimized to reduce energy consumption (Achagri et al., 2025). A 99.6% COD removal rate was reported at 1.76 kWh/m³ using recycled aluminum from cans, confirming the direct relationship between current density and COD removal (Nahla et al., 2026). A 93.00% removal rate for oil was achieved in just 90 seconds of electrolysis, with 0.022 kWh/kg of oil removed, demonstrating that short electrolysis times can drastically reduce energy consumption without sacrificing removal efficiency (Jianlong et al., 2024). Removal rates of 92.67% for COD, 92.94% for phenol, and 97.86% for color were achieved, confirming that current density is the parameter that governs the removal of multiple pollutants (Ngcobo et al., 2026).

3.2.3 Cluster 3 (Electrodes, Water Treatment, Contaminants)

This cluster groups together studies that address the component (electrodes), the application (water treatment), and the objective (contaminants). The relationship is instrumental: the electrodes are the key component of the reactor; their material (aluminum, iron, magnesium) and configuration (plates, meshes, discs, perforated) determine the efficiency of water treatment; and the contaminants (COD, TSS, turbidity, metals, oils) are the target of the treatment (Madhavan &

Antony, 2021). Without electrodes, there is no treatment, and without treatment, contaminants are not removed (Li et al., 2025).

The passivation of aluminum electrodes in water with high silica content was investigated, achieving 98% silica removal at 0.52 kWh/m³, demonstrating that the electrode material determines treatment efficiency (Yasri et al., 2022). It was demonstrated that perforated electrodes with 16 holes achieve 98.07% COD removal and 96.00% oil removal, showing that the electrode configuration directly influences contaminant removal (Li et al., 2025). A 98% removal rate for oil and grease and a 99% removal rate for COD were achieved with a polarity reversal, confirming that electrode configuration is key to the efficiency of water treatment (Madhavan & Antony, 2021). A 99% removal rate for cobalt was achieved using aluminum electrodes under optimal conditions of a current density of 15 mA/cm², a pH of 8, and 40 minutes of electrolysis, demonstrating that the electrode material is critical for heavy metal removal (Hassan & Abbar, 2025). A 98.09% COD removal rate was achieved using alternating Al-Al electrodes, indicating that the electrode configuration can be optimized to maximize contaminant removal (Movahhedtaher et al., 2024). A 94% removal rate for oil and a $98 \pm 2\%$ removal rate for turbidity were achieved using EC enhanced with cobalt ferrite, demonstrating that modifying the electrode with advanced materials improves treatment efficiency (Vieira et al., 2025).

3.2.4 Cluster 4 (Oily water, oil, demulsification)

This cluster brings together studies that address the matrix (oily water), the contaminant (oil), and the process (demulsification). The relationship is operational: oily water is the matrix under study; oil is the primary contaminant, present in the form of emulsions stabilized by surfactants and asphaltenes; and demulsification is the key process for breaking down these emulsions and separating the oil from the water. Without demulsification, the oil cannot be separated, and without separation, the water cannot be recovered (Zhang et al., 2024).

An electrolysis-enhanced coagulation (EEC) process was evaluated using a titanium anode coated with ruthenium-iridium oxide (Ti/RuO₂-IrO₂) and external aluminum chloride (AlCl₃), achieving 96.7% oil removal at 0.17 kWh/m³, demonstrating that demulsification is the rate-limiting step of the process (Jianlong et al., 2024). EC-induced foaming was investigated, achieving 95.10% oil removal and 172.90 mL of hydrogen, demonstrating that demulsification directly influences hydrogen production (Jiang et al., 2026). An oil removal rate of 93.00% was achieved in just 90 seconds of electrolysis, with 0.022 kWh/kg of oil removed, confirming that demulsification can be achieved in ultrashort times (Hu et al., 2025). A 99% oil recovery rate was reported using a combined thermochemical + EC process, demonstrating that demulsification is key to oil recovery (Zhang et al., 2024). EC was reported to reduce turbidity by 88%, TSS by 66%, and oil content by 54%, demonstrating that demulsification also reduces the turbidity of treated water (Behera et al., 2025). A 98% O&G recovery rate and a 99% COD removal rate were reported with a polarity reversal, confirming that demulsification is the process that governs oil-water separation (Madhavan & Antony, 2021).

4 CONCLUSION

The bibliometric analysis has shown a significant increase in publications on the treatment of contaminated water from the oil industry using electrocoagulation in the Scopus database, particularly between 2021 and 2026, reflecting the scientific community's growing interest in this sustainable and effective technology for the removal of oil-based contaminants.

The reviewed studies highlight the high efficiency of electrocoagulation in removing a wide variety of contaminants, such as oils, COD, TSS, turbidity, and heavy metals. Under optimal conditions, removal rates often exceed 90%, confirming the viability of the process for treating contaminated water from the oil industry.

Electrocoagulation has proven to be a flexible technology that can be adapted to different types of oily wastewater, such as produced water, refinery

effluents, and drilling mud, using various electrode materials, such as aluminum, iron, and magnesium, and by combining them with other technologies such as ultrafiltration, reverse osmosis, microbial fuel cells, and magnetic separation, thereby broadening its applicability in various industrial contexts.

Recent advances in the optimization of operating parameters have made it possible to significantly reduce energy costs and electrode consumption, making it a more sustainable option. Furthermore, its ability to generate less sludge compared to conventional methods, along with the possibility of integrating renewable energy sources, reinforces its potential to contribute to a more environmentally friendly treatment of contaminated water from the oil industry.

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