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Review paper

Electrocoagulation for industrial wastewater remediation: efficiency, operational optimization and sustainable implementation

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Abstract

Industrial wastewater often contains high concentrations of organic matter, nutrients, heavy metals, dyes, oils, and emerging contaminants, which pose significant environmental and public health risks. Identifying efficient and scalable treatment technologies has therefore become a priority for industries and regulatory agencies. Electrocoagulation (EC) has emerged as a promising method due to its operational simplicity, reduced chemical reagent requirements, and its ability to generate in situ coagulants that remove diverse pollutants. This review examines the performance, advantages, limitations, and recent advances of EC in treating industrial effluents. A structured literature search was conducted in accordance with PRISMA guidelines in Scopus, using defined inclusion and exclusion criteria. A total of 51 empirical studies published between 2014 and 2025 were analysed, covering more than twelve industrial sectors. The review compares operational parameters, pollutant removal efficiencies, energy consumption, sludge generation, and cost considerations. Results show that EC achieves consistently high removal of colour, turbidity, chemical oxygen demand, nutrients, oils, and metals across multiple industries, often outperforming conventional chemical coagulation. Nevertheless, challenges persist, including electrode passivation, energy demand, lack of standardized operational criteria, and limited pilot- and full-scale applications. Based on the comparative evaluation, the study recommends optimizing current density and pH control, integrating EC with hybrid processes, improving cost-energy models, and promoting industrial-scale demonstrations. These findings provide researchers and practitioners with an updated and comprehensive understanding of the potential and limitations of EC for sustainable industrial wastewater treatment.

Keywords
Electrochemical treatment; emerging coagulation processes; PRISMA-PICO method; contaminant removal; water purification technologies

Introduction

Industrial wastewater represents a major environmental and health challenge because its complex and varied composition depends on the processes and materials used in each industrial sector [1,2]. These effluents originate during the processing, manipulation, and transformation of resources in the production of various goods and services [3]. As productive sectors expand, so does the amount of pollutants generated, including both persistent toxic substances and emerging compounds that pose considerable risks to the aquatic environment and human health [4,5]. These pollutants include heavy metals and organic chemicals, which are often difficult to remove using conventional treatment methods [6,7].

In industry, water is used for a variety of functions, and each industrial process requires water with specific characteristics and free of contaminants [8]. However, these processes introduce new contaminants that, when discharged into a receiving waterway without adequate treatment, can significantly affect health, well-being, and the environment [9]. Therefore, industrial wastewater must undergo pretreatment to restore its initial characteristics before discharge [10].

To minimize environmental impact and protect human health, several methods have been implemented for the treatment of industrial wastewater [11,12]. However, most conventional methods have limitations, including the removal of specific contaminants and operational costs [13,14].

This has led to the search for new, efficient alternatives. Although advanced processes exist, many require high energy and chemical inputs, limiting their viability for large-scale applications [15,16]. Furthermore, growing concerns about sustainability have encouraged the development of greener technologies, such as electrocoagulation [17-19], which has demonstrated strong potential for removing persistent pollutants and reducing the use of additional chemicals [20,21], achieving significant efficiencies in industrial sectors such as textiles and metallurgy [22,23]. This process has also evolved with the integration of hybrid systems, such as electrooxidation and electroflotation [24], which has improved its ability to treat specific contaminants quickly and economically [25,26].

The pollutants present in industrial waters are of very diverse nature [27] and can be both organic (hydrocarbons or organic solvents) and inorganic (especially heavy metals), which can be found in excessive quantities [28,29]. Methods that employ electrochemical processes have shown remarkable flexibility and potential for treating these contaminants [30,31].

According to Caviedes *et al*. [32], the classification of industrial water treatment technologies depends on several factors for the removal of these contaminants. One of these technologies is electrocoagulation, a process that applies the principles of coagulation-flocculation in an electrolytic reactor [33,34], which is a container equipped with a current source and several electrodes that serve to supply destabilizing ions that replace the functions of the chemical compounds used in conventional treatments [35,36], inducing electric current in the water by means of parallel metal plates made of iron or aluminium [37-39]. In this process, contaminants in the water clump together, forming solid particles that are less soluble and less colloidal than before [40,41]. This enables them to become hydrophobic, facilitating their precipitation or flotation, thereby allowing their removal by a secondary method [42]. In recent studies, electrocoagulation has been indicated to be effective not only in reducing solids and organic matter [43], but also in the treatment of emerging compounds such as pharmaceuticals and endocrine disruptors [44,45].

Electrocoagulation is effective in removing a variety of contaminants (including oils, fats, heavy metals, colloidal organic compounds, and dyes) that are suspended, dissolved, or in emulsion form [46,47]. Furthermore, this process excels in the removal of heavy metals such as lead, chromium, and zinc, as well as organic matter, measured by biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD) [48,49]. Ismail *et al*. [50] highlighted that electrocoagulation has been particularly effective in treating effluents with high contaminant loads, achieving total dissolved solids removal of more than 90 % in laboratory tests. This method is applied to wastewater from multiple industries, such as food, electroplating, paper, tanning, steel and textile, in addition to being useful in laundries and WWTPs [51-53]. According to Hernández and Mejia [54] and Ebba *et al.* [55], the key factors that affect the efficiency of this method include pH, residence time, conductivity, type of material and separation between the electrodes, as well as the intensity of the applied current. While the efficiency of the electrodes depends on the concentration, stirring speed and type of contaminant [56,57].

In recent years, advances in electrocoagulation technology have improved its efficiency for contaminant removal [58,59]. Sludge reuse, H_2 recovery, and the use of alternative energy sources are recent advancements in electrocoagulation technology [60,61]. Furthermore, the use of hybrid systems and the integration of complementary methods, such as electrooxidation and electroflotation [62,63], have expanded the capacity of electrocoagulation to treat wastewater more quickly and economically [64,65].

Given the aforementioned, this study evaluates electrocoagulation as an effective intervention for industrial wastewater treatment, compares its efficiency and costs with alternative methods, and analyses the barriers to its implementation faced by facilities [66,67]. Through a systematic literature review, the study aims to clarify the relevant findings and inform the development of sustainable solutions for industrial effluent management.

Systematic reviews are fundamental to scientific research, as they enable the rigorous synthesis and evaluation of existing evidence on a specific topic, thereby facilitating informed decision-making [68]. By employing methodologies such as PRISMA (preferred reporting items for systematic reviews and meta- analyses) and PICO (patient, intervention, comparison, outcome) review frameworks, a structured and transparent approach to searching, selecting and analysing studies is ensured [69,70]. This not only increases the validity and reproducibility of the findings but also strengthens confidence in the conclusions derived from the review.

This approach is especially crucial in areas such as wastewater treatment, where identifying effective interventions, such as electrocoagulation, can significantly impact public health and the environment. The ability to efficiently and sustainably remove contaminants is essential to addressing current challenges in water management, contributing to environmental sustainability and community well-being. Furthermore, the systematic review identifies both advances and challenges in the application of innovative technologies, such as electrocoagulation, which can guide future research and policy. Highlighting knowledge gaps and barriers to implementation can foster more effective, locally tailored development in industrial wastewater treatment.

Experimental

Protocol and focus questions

The research questions for this review were formulated using the PICO method. This format is used in systematic review articles as it allows questions to be structured clearly and precisely. The PICO strategy facilitates the generation of diverse research questions, which in turn yield more specific and relevant results [71]. The PICO method helps to structure research questions in a systematic review through its critical components, identifies problems and translates them into a structure based on population (problem), intervention, comparison and outcome. population/ problem means: What is the problem to be addressed? Intervention refers to what action or change would affect the population/problem? Comparison means: What is the alternative to the intervention? Is there a different intervention? Outcomes refer to what is the relevant results [71]. The applied PICO strategy is presented in Table 1.

Table 1. *Description of the application of the PICO method for formulating research questions in the comparative analysis of electrocoagulation strategies for the treatment of industrial wastewater*

Population	Industrial wastewater
Intervention	Application of electrocoagulation for industrial water treatment
Comparison	Alternative water treatment methods
Result	Removal of contaminants from industrial waters

According to the PICO method, the following questions were formulated:

Q1. What types of contaminants are removed by electrocoagulation and in what types of industrial effluents is this technique applied?

Q2. What is the efficiency of electrocoagulation applied to the elimination of contaminants in industrial waters?

Q3. What are the main operational factors that affect the removal of contaminants in the electrocoagulation process?

Q4. What is the average cost per cubic meter of water treated by electrocoagulation compared to other industrial water treatment methods?

Q5. What barriers do wastewater treatment facilities face when implementing electrocoagulation technologies?

Q6. How does electrocoagulation compare with other industrial water treatment methods in terms of efficiency, costs and sustainability?

Search and selection of articles on electrocoagulation in industrial wastewater using the PRISMA methodology

To begin the search for articles in digital databases, the keywords industrial water, electrocoagulation, and treatment were used. This search was conducted in the Scopus database using Boolean operators AND and OR. A total of 839 relevant documents were obtained.

The following inclusion criteria were considered for the selection of articles that allowed answering the research questions: the keywords must appear in the title, abstract or keywords of the article, the studies must be directly related to the application of electrocoagulation in the treatment of industrial water, the articles must be in English, the articles must have been published between January 2014 and May 2025.

The following exclusion criteria were considered to ensure the quality of the review: articles that did not study electrocoagulation for industrial water treatment were excluded, documents that did not address specific research questions related to electrocoagulation were discarded, articles not directly related to electrocoagulation technology were eliminated.

Applying the aforementioned criteria, the combination of terms was structured as follows: TITLE--ABS-KEY (electrocoagulation AND ("industrial wastewater " OR "industrial wastewater") treatment")) AND PUBYEAR> 2013 AND PUBYEAR < 2026 AND (LIMIT-TO (LANGUAGE, "English"))

This search returned 197 articles from Scopus. After reviewing the titles, 77 unrelated articles were discarded, leaving 120 articles for further review. Subsequently, 45 articles were excluded after analysing the abstracts: 14 for not being related to electrocoagulation, 6 for not addressing the research questions, and 4 for not being related to wastewater treatment, leaving 51 articles to address the research questions. Figure 1 presents a diagram of the article search process for this systematic review, showing those that were selected after undergoing a search, identification and filtering process, using the PRISMA statement [72].

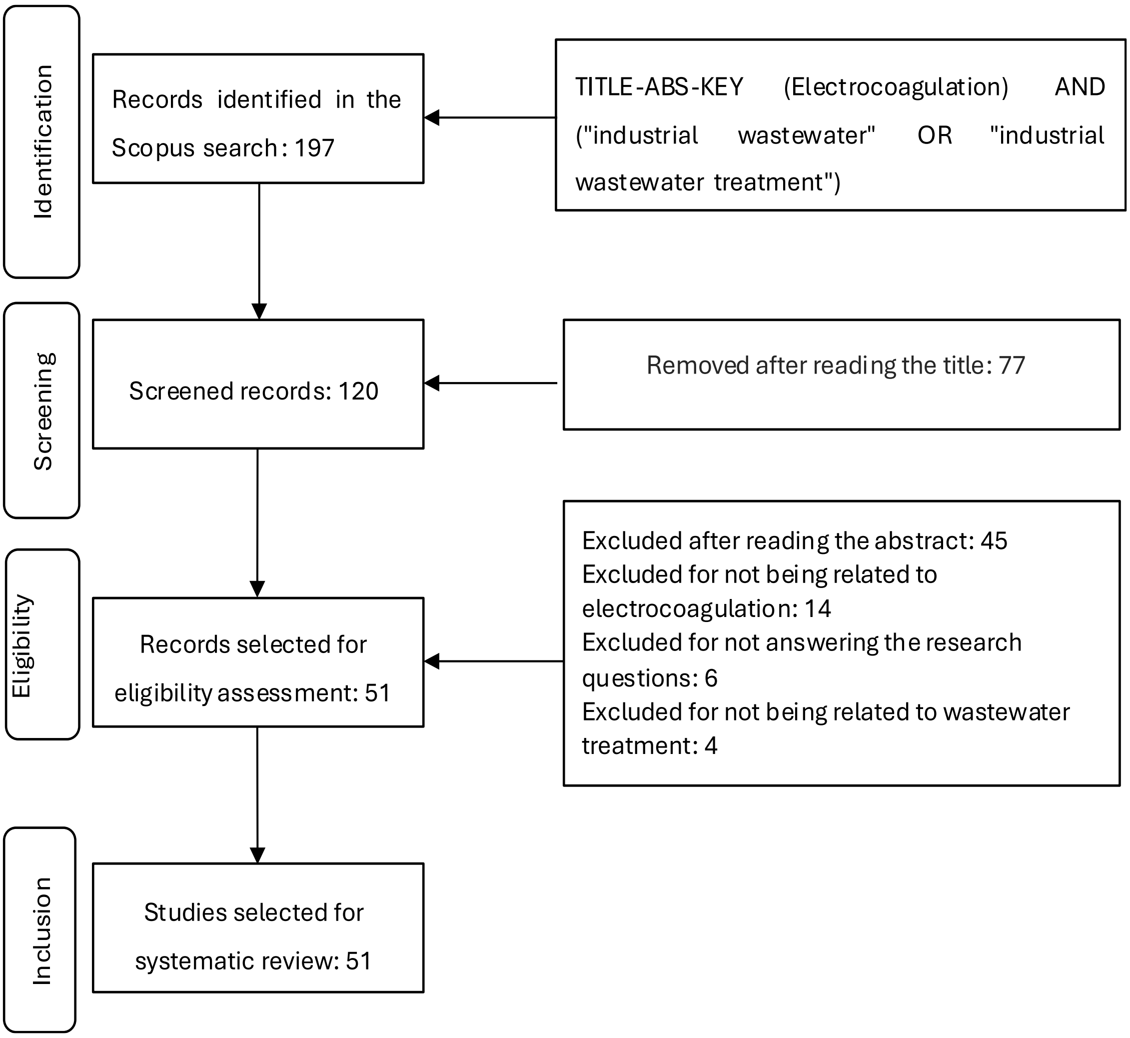

Figure 1. *PRISMA diagram of the process of identifying, selecting, and being eligible for the studies included in this systematic review*

Q1. What types of contaminants are removed by electrocoagulation and in what types of industrial effluents is this technique applied?

Electrocoagulation (EC) has emerged as a versatile tool for industrial wastewater treatment, as summarized in Table 2. This method has proven effective in removing organic pollutants, such as chemical oxygen demand (COD) and biochemical oxygen demand (BOD_5), across various industries. It has been applied in tanneries [73,74], dairy factories [75,76], palm oil processing plants [77], textiles [78], and distilleries [79,80]. Furthermore, EC is effective in removing colour and turbidity in effluents from the dairy [81], swine [82], and textile industries [78].

For heavy metals such as chromium, this method has been effective in treating tannery effluents, meeting stringent environmental regulations [73,83]. It has also demonstrated remarkable performance in removing nutrients, such as phosphorus and nitrates, from swine wastewater [82] and industrial container-washing fluids [84]. For emerging pollutants such as nanoplastics, Pawak *et al.* [85] reported impressive results using EC with aluminium electrodes in synthetic wastewater. Electrocoagulation is integrated with other technologies, such as ultrafiltration [86] or UV photolysis

[74], thereby improving its effectiveness in specific scenarios, such as palm oil mills and tanneries. This technique adapts to a variety of settings and operating conditions, delivering reliable results in removing key contaminants while complying with environmental regulations and creating opportunities for industrial water reuse across diverse industrial settings.

Table 2. *Classification of contaminants removed by electrocoagulation according to the reviewed studies (2014-2025). The table summarizes the type of contaminant, parameters evaluated, origin of the effluents, and authors who reported the efficiency of the process under different operating conditions*

Type of pollutant	Parameters	Type of industrial effluent	Ref.
Nanoplastics	Polystyrene	Synthetic wastewater	[85]
Heavy metals	Chromium (Cr^{3+})	Tannery effluents	[73,74,83]
Organic compounds	Total COD, soluble COD	Mixed wastewater from the dairy and meat industries	[87]
	Chemical oxygen demand	Tannery effluents	[73,74,83]
		Paint industry effluents	[88]
		Wastewater from the dairy industry	[75,76,81]
		Pig wastewater	[82]
		Synthetic dairy wastewater	[89]
		Wastewater from the paper industry	[90]
		Slaughterhouse wastewater	[91,92]
		Palm oil factory effluent	[77]
		Industrial container washing water	[84]
		Synthetic dairy wastewater	[93]
		Wastewater with insecticides	[94]
		Aquaculture effluents	[17]
		Distillery wastewater	[79,80]
		Textile wastewater	[78]
	Biochemical oxygen demand	Pig wastewater	[82]
		Slaughterhouse wastewater	[91,92]
		Palm oil factory effluent	[19,77]
		Aquaculture effluents	[17]
Nutrients	Nitrites (NO_2^-), nitrates (NO_3^-), sulphates (SO_4^{2-}), phosphates (PO_4^{3-})	Tannery effluents	[73,74]
	Total phosphorus (TP)	Pig wastewater	[82]
	Phosphorus	Industrial container washing water	[84]
Suspended particles	Turbidity	Mixed wastewater from the dairy and meat industries	[87]
	Suspended solids (SS)	Wastewater from the dairy industry	[75,76]
	Total organic carbon (TOC)	Wastewater from the dairy industry	[89]
	Fats and oils	Oil wastewater	[95]
		Pig wastewater	[82]
		Wastewater from the paper industry	[90]
		Slaughterhouse wastewater	[91,92]
		Container washing water	[84]
		Synthetic dairy wastewater	[89,93]
		Aquaculture effluents	[17]
		Textile wastewater	[78]
Colouring compounds	Colour	Wastewater from the dairy industry	[75,89,81]
		Slaughterhouse wastewater	[91,92]
		Aquaculture effluents	[17]
		Distillery wastewater	[79,80]
		Textile wastewater	[78]

Analysis of the contaminant table reveals that electrocoagulation is effective in removing various types of contaminants, including nanoplastics, heavy metals, organic compounds, nutrients, suspended particles, and colouring compounds. For nanoplastics, specifically polystyrene, EC has shown promising results in synthetic wastewater [85]. Regarding heavy metals, chromium has been a focus of attention in tannery effluents, where EC not only reduces its concentration but also ensures compliance with environmental regulations [73,83]. Organic compounds, as measured by COD and BOD_5, have been successfully treated in wastewater from the dairy, meat, and paint industries, demonstrating the versatility of EC across industrial sectors. Furthermore, the removal of nutrients such as nitrites, nitrates, and phosphates from swine wastewater and container wash liquids is crucial for preventing eutrophication in water bodies. EC's ability to remove suspended particles and colouring compounds from textile industry and slaughterhouse effluents highlights its importance in improving the quality of treated water. In short, electrocoagulation presents a comprehensive and effective solution for industrial wastewater treatment, addressing a wide range of contaminants and contributing to environmental sustainability.

Q2. What is the efficiency of electrocoagulation applied to the removal of contaminants in industrial waters?

Table 3 provides an overview of how various studies have evaluated the efficiency of electrocoagulation in removing contaminants from industrial wastewater. For example, Sameh *et al.* [74] achieved an impressive 94.1 % COD reduction efficiency by combining electrocoagulation with UV photolysis; this dual approach proved superior to either method alone. Similarly, El-Naggar *et al.* [94] took electrocoagulation to the next level by introducing a reactor with an innovative serpentine tube anode, achieving complete (100 %) COD removal from insecticide-contaminated wastewater.

In the paint industry, Aguilar [88] developed a laboratory-scale reactor that achieved 87 % COD removal, while Sanni et al. [84] combined electrocoagulation and electrooxidation to achieve 97 % and 95% COD and phosphorus removal, respectively.

Table 3. *Summary of reported removal efficiencies for electrocoagulation in different industries. Includes the main experimental configurations (electrode type: Al^{3+}/Fe^{2+}/Zn^{2+}; monopolar/bipolar arrangements; pH, time and current density conditions) and the type of contaminant treated in each study*

Pollutant	Electrocoagulation method	Efficiency, %	Description	Ref.
COD	Electrocoagulation and UV photolysis in sequence	94.1	Tannery wastewater was studied. A combined treatment of electrocoagulation and UV photolysis reduced COD, meeting limits for discharge into public sewers. The UV+EC sequence showed greater efficiency than the individual methods (85.7 % and 55.9 %, respectively).	[74]
	Electrocoagulation on a laboratory scale	87	An EC reactor was designed to treat wastewater from the paint industry, achieving COD removal in compliance with environmental regulations.	[88]
	Electrocoagulation in a new reactor	100	Evaluation of an innovative electrochemical reactor with a serpentine tube anode for remediating wastewater with insecticides. Efficiency influenced by concentration, pH, NaCl, and temperature.	[94]
COD, phosphorus	Electrocoagulation (EC) and Electrooxidation (EO)	COD: 97 Phosphorus: 95	The combination of EC and EO improved phosphorus and COD removal in industrial wastewater, meeting discharge regulations.	[84]
COD, BOD_5	Integrated photovoltaic electrocoagulation system	COD: 91 BOD_5: 96	The photovoltaic system integrated with electrocoagulation effectively reduced COD and BOD_5 in the treatment of palm oil factory effluent, improving efficiency by harnessing solar radiation.	[77]
	Integration of electrocoagulation and ultrafiltration (UF) with bipolar electrodes	COD: 96.8 BOD_5: 96	The integration of electrocoagulation (with bipolar electrodes) and ultrafiltration was investigated for the treatment of palm oil mill wastewater (POME). The optimal configurations (2A-2C-2B) achieved high removal efficiencies with reduced electrode consumption.	[19]
Nanoplastics (polystyrene)	Electrocoagulation with aluminium electrodes	95.4	Nanoplastics were removed from synthetic wastewater using CE with aluminium electrodes. The nanoplastics and coagulants formed an easily removable foamy layer.	[85]

Pollutant	Electrocoagulation method	Efficiency, %	Description	Ref.
Heavy metals, COD, nitrites, nitrates, sulphates, phosphates	Electrocoagulation on a laboratory scale	Cr^{3+}: 52.8 COD: 36 NO_2^-:99.6 NO_3^-:99.4 SO_4^{2-}:92.9 PO_4^{3-}:99.1	An electrocoagulation system for treating tannery effluents in Villapinzón, Colombia, achieved high levels of contaminant removal and met environmental regulations.	[73]
Total COD, soluble COD, turbidity	Batch type electrocoagulation with 13 iron electrodes	COD: 96 Turbidity: 94	EC applied to wastewater from the dairy and meat industries achieved high COD and turbidity removal in 60 min with 13 electrodes, although conductivity and pH increased.	[87]
COD, colour, turbidity	Laboratory-scale electrocoagulation (aluminium electrodes)	COD: 93 Colour: 97 Turbidity: 99.8	Electrocoagulation with aluminium electrodes was used to treat dairy wastewater, achieving high contaminant removal under optimal conditions, complying with Cuban regulations.	[75]
	Electrocoagulation with iron electrodes	COD: 96.36 Colour: 94.90 Turbidity: 99.98	Electrocoagulation with iron electrodes was used to treat dairy wastewater. Significant reductions in turbidity, colour, and COD were achieved under pH 4.5, 60 min of treatment, and a current of 1.5 A.	[81]
COD, turbidity, Suspended solids (SS)	Electrocoagulation with zinc electrodes	COD: 50.4 Turbidity: 99.8 SS: 73.4	Treatment with zinc electrodes in dairy wastewater achieved high removal of turbidity and suspended solids, with moderate COD reduction, under low pH conditions (3.0) and 10 minutes of electrolysis.	[76]
SS, COD, TP, BOD_5	Electrocoagulation with iron anode	SS: 98.5 TP: 99.5 COD: 50.6 BOD_5: 98.5	In the treatment of swine wastewater, electrocoagulation with an iron anode achieved high removal efficiencies of suspended solids and total phosphorus, improving the biodegradability of the effluents by increasing the BOD_5/COD ratio.	[82]
TDS, turbidity, TOC, COD	Electrocoagulation with iron electrodes	TDS: 51 Turbidity: 65 TOC: 68 COD: 70	Treatment of paper industry wastewater with iron electrodes reduced TDS, turbidity, TOC and COD under optimal conditions (pH 8, 60 min, 20 V).	[90]
COD, turbidity, fats and oils, chromium, nitrate, phosphate, sulphates	Electrocoagulation with aluminium electrodes	COD: 84 Turbidity: 98 Fats-oils: 97 Cr^{3+}: 98 NO_3^-: 68 PO_4^{3-}: 100 SO_4^{2-}: 79	Electrocoagulation was applied to tannery wastewater with aluminium electrodes and effectively removed contaminants, achieving up to 100 % phosphate removal and 98 % chromium removal.	[96]
COD, colour, turbidity, BOD_5, oils and fats	Electrocoagulation with aluminium electrodes (batch and continuous mode)	COD: 95 Colour: 99 Turbidity: 99 BOD_5: 97 Oils and fats: 95	In the treatment of slaughterhouse wastewater, electrocoagulation with aluminium electrodes achieved high removal efficiencies, with an operating cost of $1.5 m³.	[91]
COD, TSS, colour	Electrocoagulation and peroxidation	COD: 97.89 SST: 99.31 Colour: 98.56	Optimization of wastewater treatment from poultry slaughterhouses using aluminium electrocoagulation and peroxidation, complying with international regulations.	[92]
COD, turbidity	Electrocoagulation with Al and Al-AU4G electrodes	COD: 58 Turbidity: 99	Comparative evaluation of pure aluminium and Al-AU4G alloy electrodes in the treatment of synthetic dairy wastewater. The alloy electrodes showed better performance.	[93]
COD, BOD_5, turbidity, colour	Electrocoagulation - flocculation	COD: 86.4; BOD_5: 76.9 Turbidity:87.87 Colour: 73.56	Von densification theory. Smoluchowski.	[17]
COD, colour	Electrocoagulation (batch recirculation)	COD: 99.90 Colour: 100	Treatment of distillery wastewater using electrocoagulation with recirculation. Energy consumption: 7.73 kWh/m³.	[79]
Cephalexin (CFX)	Electrocoagulation	93.54	Decontamination of pharmaceutical wastewater using optimized response surface method (RSM-CCD). Reaction time was crucial.	[97]
Ca^{2+}, Sr^{2+}, Na^+, COD	Electrocoagulation with aluminium electrodes	Ca^{2+}: 88 Sr^{2+}: 77 Na^+: 26 COD: 24	The study evaluated electrocoagulation for the treatment of a saline reverse electrodialysis effluent (RED-C) in a petroleum refinery,	[98]
COD, turbidity, solids (fixed, dissolved and suspended)	Electrocoagulation with zinc electrodes under real-life conditions	COD: 50.4 Turbidity: 99.8 Total fixed solids: 24.2 Total suspended solids: 73.4 Fixed dissolved solids: 64.6	The use of zinc electrodes in a glass reactor was evaluated for the treatment of wastewater from a small dairy. Although significant reductions were achieved, negative effects such as increased TFS were observed.	[89]
COD, colour, turbidity	Electrocoagulation with metal electrodes	COD: 63.05 Colour: 99.07 Turbidity:96.31	A comparative study was conducted between chemical coagulation (CC) and electrocoagulation (EC) to treat real textile wastewater in Tunisia. The EC-treated water met Tunisian discharge standards and showed potential for industrial reuse.	[99]

Another notable study is that of Mohamad *et al.* [77], where an integrated photovoltaic electrocoagulation system effectively reduced COD and BOD_5 in palm oil industry wastewater, reaching efficiencies of 91 and 96 %, respectively. Along the same lines, Aryanti *et al*. [19] investigated the combination of electrocoagulation and ultrafiltration, achieving COD and BOD_5 removal efficiencies above 96 % in palm oil wastewater by optimizing electrode use. Studies on nanoplastic removal, such as that of Pawak *et al.* [85], highlight the versatility of electrocoagulation. This study removed more than 95 % of nanoplastics in synthetic wastewater using aluminium electrodes, a critical application in the current context of plastic pollution.

Studies agree that electrocoagulation, often combined with other methods such as UV photolysis, electrooxidation, or ultrafiltration, offers a robust solution for removing a wide range of contaminants, from organic matter to heavy metals and nanoplastics. Each research project offers a unique approach, tailoring process conditions to maximize efficiency, comply with environmental regulations, and, in some cases, improve energy sustainability.

Figure 2 presents the results of the efficiency of electrocoagulation in the removal of contaminants in industrial waters, according to the studies described in Table 3. First, an impressive 94.58 % turbidity removal rate is observed, indicating that the process is highly effective in clarifying water. Colour removal is next, at 94.41 %, reflecting a significant improvement in the water's appearance. In third place is BOD_5 removal, at 91.47 %, suggesting a considerable improvement in the biodegradability of the treated water. Nutrients were removed by 92.5 %, helping to prevent environmental problems such as eutrophication. Furthermore, the removal of suspended particles reached 88.54 %, demonstrating the process's ability to reduce undissolved solids. Finally, COD (chemical oxygen demand) was reduced by 78.04 %, reflecting effective removal of the organic load in the treated water, albeit at a slightly lower percentage than for other pollutants.

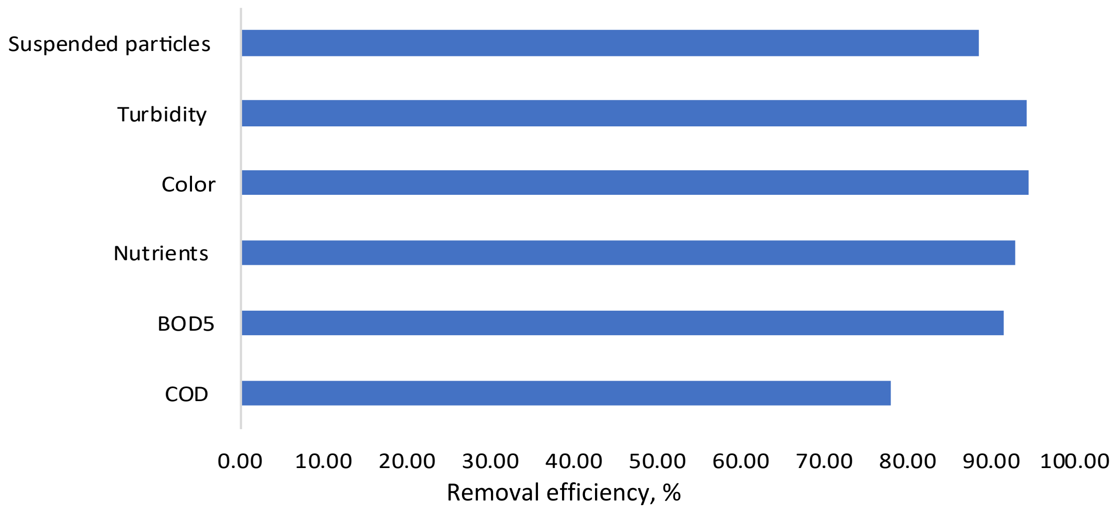

Figure 2. *Average contaminant removal efficiency by electrocoagulation, calculated from the studies included in the review (n = 51)*

Composition and temporal variability of wastewater treated by electrocoagulation

The composition of industrial wastewater treated by electrocoagulation is highly variable and depends directly on the industry type, inputs used, and operating conditions. Several studies included in this review show that these effluents can contain high organic matter loads (COD and BOD_5) in the dairy, meat, textile, and palm oil industries [75-77,81,87]. Similarly, sectors such as tanneries and metallurgy exhibit heavy metals, especially chromium, which reach high concentrations and require specific treatment [73,83]. Other effluents, such as those from slaughterhouses, distilleries, and paper mills, include high levels of turbidity, colour, suspended solids, fats and oils [82,89,91]. Nutrients such as phosphates, nitrates, and nitrites are also found in swine industries and industrial washing processes [82,84]. This compositional diversity demonstrates the versatility of electrocoagulation to treat complex matrices with organic, inorganic and emerging contaminants such as nanoplastics [85].

It is important to note that the composition of industrial effluents does not remain constant over time. Parameters can vary between periods due to fluctuations in production, changes in product formulations, variability in the quality of raw materials, and operational adjustments within industrial plants. These seasonal or production variations directly affect the pollutant load and, therefore, the efficiency and optimal operating conditions of electrocoagulation [87,90]. Recognizing this variability is essential to ensure proper system design and operation in real-world treatment scenarios.

Q3. What are the main operational factors affecting contaminant removal in the electrocoagulation process?

According to a review of various studies, several factors influence the removal of a wide range of contaminants in the electrocoagulation process. These factors significantly affect the efficiency of this method, including the formation and behaviour of coagulants and their interactions with contaminants in wastewater [99].

The main operational factors that affect contaminant removal in the electrocoagulation process are presented in Table 4. Among the factors that have stood out most is the current density, defined as the electric current per unit electrode area (A/m^2). This factor directly affects the rate of electrode dissolution and the formation of coagulants. Adequate current density values can optimize the electrocoagulation process. A very high value can decrease the efficiency of the current [56]. The type or material of the electrodes is another important factor; a variety of electrode materials have been used in the electrocoagulation process, which are iron (Fe^{2+}), copper (Cu^{2+}), aluminium (Al^{3+}), stainless steel, zinc (Zn^{2+}), and graphite, with iron (Fe^{2+}) and aluminium (Al^{3+}) being the most common materials because they can generate hydroxides that absorb contaminants [73].

The pH of the wastewater is essential for the formation of coagulants and the precipitation of contaminants. According to Lopes *et al.* [100], the appropriate pH is important to ensure treatment efficiency and the solubility of metal hydroxides, since Fe and Al exhibit greater efficiency under different pH conditions. Treatment time is an essential factor in the electrocoagulation process. If the time is insufficient, coagulant generation can be limited. On the other hand, an extended period can lead to increased electrode and energy consumption, and the electrocoagulation process may be inefficient [91].

Another important factor is the spacing between the electrodes. If the area between the anode and cathode is too large, it can decrease the removal efficiency and increase energy consumption. Ideally, a small distance between the electrodes would reduce the process's energy consumption [79,93]. In addition, the influence of temperature on removal efficiency was highlighted, although to a lesser extent, and it depends on the contaminant removal mechanism. An increase in temperature can have negative effects on the removal efficiency of contaminants [17]. Table 4 summarizes the main operational factors affecting contaminant removal in the electrocoagulation process, identified in the review.

Table 4*. The main operational factors influencing electrocoagulation efficiency, compiled from the reviewed studies, are described. Experimental ranges, the effect of each variable, and the most relevant conclusions regarding optimization are also presented*

Operational factors	Description	Ref.
Current density	In the electrocoagulation process, the reaction rate is controlled by the applied current density. Removal efficiency increases with increasing current density. According to the literature, the current density ranges from 4 to 180 mA $cm^{-2.}$	[98]
	In this study, it was shown that increasing the current density from 5 to 10 mA/cm^2 slightly decreased the contaminant concentration. Using a higher current density showed improved removal rates.	[97]
	Several subparameters depend on this factor, such as coagulant dosage rate, bubble production rate, and floc size and growth. Higher current density results in greater contaminant dissolution at the anode, increasing removal efficiency.	[60]
	This study indicates that current density affects removal efficiency and energy consumption. Adequate current density prevents the generation of excess hydrogen and ensures efficient floc formation.	[89]
	This study mentions that current density is a factor that directly affects the generation of metal ions from iron electrodes.	[90]
	This article analyses that, at higher current densities, contaminant removal increases, since it determines the rate of electrode dissolution and coagulant generation.	[101]
	During the investigation, the system operated at a constant current density. As the current density increases, the amount of dissolved cations in the anode increases, and therefore the amount of flocculant removing contaminants.	[83]
	This study mentions that higher current densities improve the removal of contaminants such as COD but can increase energy costs and generate unwanted byproducts.	[92]
	Current density has a significant impact on electrocoagulation; increased current causes anode disintegration, resulting in increased precipitation and bubble production, leading to increased flocculation and coagulation, and therefore increased removal.	[102]
Type of electrodes	Electrode material selection is one of the parameters that affects process performance and cost. Al and Fe electrodes are generally preferred due to their easy availability, low cost, and high dissolution rates.	[98]
	In this study, zinc electrodes are used, which are effective in removing contaminants, as they form metal complexes that coagulate suspended particles.	[89]
	For this study, iron electrodes were used, which are effective in treating organic and inorganic compounds, and their ability to generate ferric hydroxides, which act as coagulating agents, is notable.	[90]
	It is mentioned that several types of electrodes were used, however, aluminium electrodes were most effective for removing turbidity and phosphates, and iron electrodes for removing heavy metals.	[101]
	This article mentions that choosing the right electrode material for electrocoagulation is very important. Iron and aluminium, which are generally inexpensive, readily available, and effective, are the most common electrode materials.	[83]
	It is mentioned that iron and aluminium, which are the most commonly used electrode materials, have higher efficiencies under different pH conditions.	[81]
	Aluminium electrodes are used in this study because they are effective in removing organic matter. The use of aluminium is notable for its ability to generate flocs that trap suspended solids and fine particles.	[92]
	Al and Fe electrodes are cited as the most used materials in electrocoagulation because they are inexpensive, nontoxic, readily available, and have proven reliable. Researchers observed that the Al^{3+} electrode was most effective at reducing COD in wastewater.	[102]
pH of wastewater	The pH influences the distribution of Al^{3+} and Fe^{2+} and therefore determines the type of metal hydroxide cations in electrocoagulation and determines the interaction between the coagulants formed in the solution.	[98]
	Removal efficiency is generally best achieved at neutral pH using aluminium electrodes. Low pH solutions inhibit the electrocoagulation process.	[97]

Operational factors	Description	Ref.
pH of wastewater	In this study, the results showed that the optimal pH value is between 6 and 7, as metal hydroxides are produced and, as a result, the removal efficiency is improved.	[60]
	This article indicates that a slightly alkaline pH favours the formation of zinc hydroxides and directly influences process performance.	[89]
	In this article, the pH range was optimized to maximize contaminant removal, and the results indicated that a slightly acidic or neutral pH favours the formation of coagulant species such as ferric hydroxides.	[90]
	It should be noted that the optimal pH range depends on the type of electrode used during electrocoagulation, ranging from 5 to 8 for aluminium and slightly higher for iron.	[101]
	The correct choice of pH is essential to ensure treatment efficiency. The experiment in which the best values in parameter reduction were obtained presented a final pH of 7.35.	[100]
	According to the results of this study, optimal pH ranges between 6 and 8 were found to maximize the removal of COD and phosphorus in wastewater.	[92]
Treatment time	Time influences the concentration of metal ions produced by the electrodes to remove contaminants. As time increases, the concentration of ions and their hydroxide flocs will increase, resulting in increased contaminant removal efficiency.	[78]
	Time is related to energy consumption during the process. According to the tests conducted in this study, longer operating times equate to higher removal rates. Satisfactory removal rates were observed in the range of 90 to 120 minutes.	[97]
	According to this study, as electrocoagulation time increases, removal efficiency improves and then becomes constant. The highest removal efficiencies were achieved at 60 minutes.	[60]
	According to experimental tests, a longer operating time improves the efficiency of the electrocoagulation process, as it ensures the formation and sedimentation of flocs.	[90]
	The results showed that at the end of the 60-minute treatment period, oil and grease, chromium, and phosphate from the wastewater could be removed from the water very quickly.	[83]
	This article mentions that the best results for time were obtained at 60 min, for the removal of contaminants.	[100]
Distance between electrodes	It has been shown in the literature that when the distance between electrodes increases from 1 to 3 cm, the contaminant removal efficiency decreases from 98.59 % to 90.43 %.	[78]
	The researchers demonstrated that, to treat effluents with high electrical conductivity, the distance between the electrodes can be increased to reduce energy consumption. The optimal distance between electrodes is 5 mm.	[60]
	It is noted that the distance between the electrodes directly influences the amount of coagulant generated, since a greater distance allows for greater generation of active species.	[101]
	This study mentions that the relationship between the area of the electrodes and the volume of treated water affects the efficiency of the process.	[92]
	This study demonstrates that with a greater distance between the electrodes, the time for agglomeration of the produced metal hydroxide is sufficient, with less degradation of the flocs and, therefore, increasing the removal efficiency.	[102]
Effluent temperature	In experiments, the best removal rates were observed at 20°C and 30°C. Higher temperatures, such as 40°C, limited contaminant removal efficiency, as more compact flakes formed and deposited on the plate surface, causing electrode passivation.	[97]

Q4. What is the average cost per cubic meter of water treated by electrocoagulation compared to other industrial water treatment methods?

According to Dobrosz *et al.* [103], the cost per cubic meter of water treated using the electrocoagulation method varies depending on several factors, such as the electrode material, wastewater composition, energy costs, and chemical inputs used. This study reports an average treatment cost of 2.06 USD m^{-3} for electrocoagulation of wastewater from the soluble coffee industry. This value accounts for energy consumption, electrode wear, and sludge disposal, using iron electrodes as the anodes and stainless steel as the cathodes. Compared with the advanced oxidation method, electrocoagulation has lower operating costs due to its lower energy consumption and reagent use. For example, the electrocoagulation-anodic oxidation process, used in this study, had operating costs of 7-12 USD m^{-3}.

According to an experimental study conducted in a sausage industry, the average cost of treating industrial wastewater using electrocoagulation is \$0.23 per cubic meter (USD m^{-3}), while the cost of chemical coagulation is 0.37 USD m^{-3}. This means that electrocoagulation has significantly lower operating costs, accounting for approximately 62.16 % of chemical coagulation costs. It is worth noting that this analysis was conducted for a pilot-scale plant with a treatment capacity of 36 m^3 day^{-1} [104]. Chemical coagulation costs include the cost per reagent (0.33 USD m^{-3}) and the cost per agitation (0.04 USD m^{-3}), yielding a total of 0.37 USD m^{-3}. On the other hand, in the case of electrocoagulation, the operating costs considered are the cost per energy (0.18 USD m^{-3}) and the cost of electrodes (0.05 USD m^{-3}), providing a total of 0.23 USD m^{-3} [104].

The economic evaluation of electrocoagulation indicated an average treatment cost of 3 USD m^{-3} for a small-scale operation handling 3000 L of wastewater per day. This study demonstrated that electrocoagulation (EC) is a promising technique for recovering and regenerating water from anaerobic digestion effluent. These characteristics make EC technology applicable, either alone or in combination with other technologies, for a wide range of wastewater treatment applications [66].

In a recent study on the treatment of livestock slaughterhouse wastewater using continuous electrocoagulation with aluminium electrodes, removal efficiencies of 95 % for COD, 99 % for colour, 99 % for turbidity, 97 % for BOD_5, and 95 % for oils and grease were achieved. Under these optimized conditions, electrode consumption was 0.6 kg m^{-3}, while energy consumption was 0.87 kWh m^{-3}. As a result, the total operating cost of the process was estimated at approximately 1.5 USD m^{-3}, positioning electrocoagulation as a technically efficient and economically competitive option for the treatment of highly contaminated industrial wastewater [91].

The estimated operating cost of the electrocoagulation process applied to the treatment of dairy industry wastewater was 1.04 USD m^{-3}, demonstrating its technical and economic viability, especially compared to conventional methods that may entail higher operating costs or additional chemical requirements. In addition to its low cost, the process demonstrated high efficiency in removing COD, turbidity, and total solids, establishing itself as a promising alternative for this type of industrial effluent [81].

Falcón *et al*. [105] investigated the treatment of synthetic wastewater contaminated with aspirin using electrocoagulation. Operating costs ranged from 0.73 to 3.15 USD m^{-3}, depending on factors such as the applied voltage and treatment time. These results indicate the influence of operating conditions on the economic viability of the process.

Q5. What barriers do wastewater treatment facilities face when implementing electrocoagulation technologies?

Numerous laboratory-scale studies on contaminants have been conducted; however, for any method to be industrially viable, electrocoagulation technologies must be scaled up. This expansion presents several challenges, including deterioration of cathode performance due to chemicals, reduction of anodic biofilm, short-term stability, fouling, chemical alteration, process optimization, and system clogging by contaminant solids [102].

Several studies indicate that implementing this technology is expensive, as it requires substantial electrical energy, particularly when treating effluents with high levels of contaminants, thereby increasing facility operating costs. Furthermore, the intensive use of electrodes, such as aluminium and iron, during the electrocoagulation process causes their degradation, reducing their service life and, consequently, leading to higher maintenance and replacement costs [86].

Current density is a critical parameter for the efficiency of the electrocoagulation process, as it directly influences floc formation, the anode dissolution rate, and hydrogen bubble production. Increasing the current density from 0.76 to 3.81 mA cm^{-2} at a constant pH of 6 and a reaction time of 5 minutes increased the removal efficiency from 68 to 88 %. However, higher current densities also increase energy consumption and anode wear, thus representing a considerable economic barrier [106].

Electrocoagulation, by removing impurities from water, generates gases and sludge that are classified as waste and incur high disposal costs. However, these sludges contain valuable materials, such as nutrients and metals from both the treated impurities and the electrodes used (aluminium or iron). Despite their potential, the management and recovery of these residues are still poorly developed. Research highlights the importance of optimizing their reuse in applications such as fertilizers, adsorbents, and construction materials, in line with the principles of the circular economy and environmental regulations that aim to reduce the impact of generated waste [107].

Q6. How does electrocoagulation compare with other industrial water treatment methods in terms of efficiency, costs and sustainability?

Electrocoagulation is a water treatment technique that has been evaluated against other methods to understand key aspects of contaminant removal. This method has demonstrated advantages in removing parameters such as COD and BOD_5 compared with alternatives, including chemical coagulation and electro-Fenton. Regarding costs, in the study by Gaied *et al*. [108] and the study by Gasmi *et al*. [98], electrocoagulation is the most cost-effective method compared to chemical coagulation and electro-Fenton treatments [98]. Table 5 summarizes recent studies on the efficiency and costs of electrocoagulation relative to alternative methods.

In the last four years, electrocoagulation (EC) has undergone a significant technological evolution, driven by advances in reactor design, hybrid treatment systems, and sustainable energy integration. Recent studies (2021-2025) highlight a transition from conventional EC setups toward next-generation modular and high-efficiency reactors, including serpentine-flow anode systems, bipolar configurations, and optimized hydrodynamic designs that enhance mass transfer and coagulant production. Novel electrode materials, such as aluminium alloys, conductive composites, and coatings designed to reduce passivation, have also improved long-term operational stability and reduced maintenance requirements. Hybrid systems have emerged as a central trend. Between 2022 and 2025, EC has been increasingly combined with electrooxidation, ultrafiltration, UV-photolysis, biological polishing stages, and Fenton-based advanced oxidation, achieving synergistic improvements in COD, BOD_5, turbidity, and persistent contaminant removal. These innovations address limitations of standalone EC processes, especially when treating complex industrial effluents such as pharmaceutical wastewater, pesticide-laden discharges, and high-strength agro-industrial waste streams. Energy sustainability has also become a major research focus. From 2021 onward, several studies reported the successful integration of photovoltaic-powered EC, energy recovery systems from hydrogen gas byproducts, and optimized current profiles to reduce operational costs. Additionally, advances in modelling, such as artificial intelligence, machine learning, and response surface methodology, have enhanced process optimization and predictive control, reducing electrode consumption and energy demand. These recent developments show that electrocoagulation is evolving into a highly tuneable, scalable, and energy-efficient technology, moving beyond traditional applications and enabling its deployment in real industrial contexts with improved performance and lower costs.

Table 5. *Comparison between electrocoagulation and alternative methods of industrial wastewater treatment, considering removal efficiency, costs, operating conditions and reference studies included in the review*

Aspect	Main method	Alternative method	Ref.
	Electrocoagulation	Chemical coagulation	[109]
Description	Gelatin plant effluents, with high organic load and suspended solids, were treated with both methods, showing limitations in traditional secondary methods.		
Efficiency	COD Removal: 73.6 %	COD Removal: 55.6 %	
Costs	Requires specialized equipment (electrodes, current source) and variable energy costs	Dependent on the purchase of sales of aluminium as an input.	
	Electrocoagulation	Electro-fenton and advanced electrooxidation	[108]
Description	This study focuses on evaluating the efficiency of organic matter and microbial load removal, achieving significant reductions in BOD_5, COD and microorganism levels		
Efficiency	The EC destroyed a large number of germs.	COD removal by these methods were: 56 and 14 %.	
Costs	13.8 € m^{-3}	17.3 and 21.8 € m^{-3}	
	Electrocoagulation	Peroxy-EC and peroxicogulation processes	[110]
Description	This study compared the 3 methods for the treatment of wastewater with purified terephthalic acid		
Efficiency	Maximum COD removal: 60.76 %	Maximum COD removal: 73.91 and 66.68 % respectively.	
Costs	Low	Peroxy - EC: moderate	
		Peroxicogulation: more expensive due to additional inputs and complexity.	
	Electrocoagulation	Chemical coagulation	[98]
Description	This study compares the efficiency and operating costs of two textile wastewater treatment methods. It examines their ability to remove various contaminants		
Efficiency	COD reduction: 90 %	COD reduction: 85 %	
	Colour: > 98 %	Colour: 95 %	
	Turbidity: Efficient removal.	Turbidity: significant decrease.	
Costs	0.35 USD m^{-3} of treated water	0.45 USD m^{-3} of treated water	
	Electrocoagulation	Photo-assisted chemical oxidation	[111]
Description	This article compares both technologies for the decolorization of a reactive textile dye		
Efficiency	> 99 %	>99 %	
Costs	Operating costs: 0.64 USD kg^{-1} of COD removed	Operating costs: 1.94 USD kg^{-1} of COD removed	
	Electrocoagulation	Electrocoagulation-flocculation	[112]
Description	This article analyses the efficiency and costs of both methods for urban wastewater treatment. The study evaluates the removal of various pollutants such as COD and BOD_5		
Efficiency	COD: 85 % removal	COD: 85 %	
	BOD_5: 84 %	BOD_5: 86 %	
	SST: 94 %	SST: 95 %	
	N: 63 %	Improves phosphorus removal by 99 % in less time	
Costs	0.9 USD kg^{-1} of COD	0.7 USD $k^{-1}g$ of COD	
	0.35 USD kg^{-1} of phosphorus	0.3 USD kg^{-1} of phosphorus	

Potential for electrode regeneration and reuse for more sustainable electrocoagulation

The regeneration and reuse of sacrificed electrodes are key factors in optimizing the operational sustainability, energy efficiency, and economic viability of EC systems. Although EC is valued for its ability to remove contaminants effectively, its long-term performance is compromised by electrode passivation and the need for frequent replacement of metal plates [113].

In passivation mechanisms and regeneration strategies, one of the main challenges is the accumulation of oxide layers, precipitates, or organic films on the electrode surface, as these reduce the active area, increase electrical resistance, and decrease faradic efficiency [114-115]. Recent studies show that periodic polarity reversal (polarity reversal, PR) is highly effective at removing these passive layers in situ, restoring the active surface of the electrode [115].

For example, research using aluminium electrodes demonstrated that polarity reversal reduces passive film buildup, optimizes faradic efficiency, and improves process sustainability, all while maintaining treatment capacity and reducing energy dissipation [116]. Similarly, in silica-rich waters, very short reversal cycles (10 s) have been reported to produce softer, more easily removable deposits, in contrast to hard deposits under direct current (DC) operation [117].

Furthermore, chemical regeneration has been successfully applied: using mild acid solutions (*e.g.* 1 to 5 % HCl or citric acid), the passive layer can be removed without damaging the electrode's structural integrity, recovering a significant portion of its activity [113]. This technique is complemented by mechanical cleaning, such as brushing or sandblasting, which is particularly useful in industrial installations due to its low cost and ease of implementation [118].

Another way to improve electrode durability is to use protective alloys or coatings. Composite electrodes, such as Fe-Al or Al-Ti, have proven more resistant to passivation, withstanding multiple regeneration cycles with minimal loss of efficiency [119]. Chemical or physical protection through coatings can slow the rate of degradation and extend service life, directly contributing to the sustainability of the process.

From a life cycle assessment (LCA) perspective, the reuse of regenerated electrodes significantly reduces the generation of metallic waste and associated operating costs. A recent study evaluated the use of titanium anodes for manganese removal and demonstrated not only efficiencies approaching 96 % but also moderate environmental impacts, as assessed by carbon footprint and potential toxicity [120].

More broadly, systematic regeneration can recover between 70 and 95 % of the electrode's original performance, depending on the method used and the type of effluent treated [113]. This translates into lower material consumption, reduced energy demand per unit of contaminant removed, and lower costs associated with electrode replacement.

Although the aforementioned strategies show great potential, technical and economic challenges remain for their implementation at an industrial scale. Polarity reversal, for example, requires precise switching equipment and control systems, increasing reactor complexity and capital costs [121]. Furthermore, continuous chemical regeneration can gradually degrade the electrode structure or alter its microstructure, necessitating specific evaluation for each wastewater type [116]. Advanced coatings and more sophisticated electrode materials have also been proposed to improve durability; however, their adoption in real-world industrial applications remains limited, and their cost requires further analysis [122].

Knowledge gaps

Electrocoagulation, although presented as a promising solution for industrial wastewater treatment, faces several challenges and knowledge gaps that limit its implementation and optimization. One of the main challenges is the lack of industrial-scale studies, as most research has been conducted under controlled laboratory conditions that do not reflect the complexities and variability of industrial operations. This creates uncertainty about the effectiveness of the process under real-life conditions, where factors such as water composition, variability in contaminant load, and operating conditions can significantly influence results. Furthermore, the management of generated byproducts, such as sludge, represents another significant gap; although techniques for its reuse have been identified, further research is still required to develop efficient and sustainable methods that minimize the environmental impact of this waste. Another challenge is the high initial installation and operation costs of electrocoagulation systems, which can hinder their widespread adoption, particularly in resource-limited industries. The lack of technical knowledge and training in the use of this technology also hampers its implementation, suggesting the need for training and education programs for professionals in the sector. Furthermore, proper electrode selection and control of critical operational factors, such as pH and electric current, are essential to maximize process efficiency but are often not adequately considered in existing studies. Integrating electrocoagulation with other treatment methods, such as electrooxidation and electroflotation, presents an opportunity to improve efficiency and reduce costs, but further research is required to evaluate the feasibility and effectiveness of these hybrid systems.

Likewise, the lack of life-cycle analyses comparing the environmental impact of electrocoagulation with other treatment methods limits our understanding of its long-term sustainability. Collaboration between academia and industry is crucial to address these knowledge gaps and develop innovative solutions that optimize the use of electrocoagulation in wastewater treatment. Promoting additional research on process optimization, long-term cost assessments, and training of professionals in the field can maximize the positive impact of this technology on wastewater management. In summary, although electrocoagulation offers great potential for improving sustainability in industrial wastewater treatment, it is critical to address existing challenges and knowledge gaps to facilitate its adoption and maximize its benefits. This includes conducting industrial-scale studies, developing efficient methods for byproduct management, reducing operating costs, and fostering training and collaboration within the sector. Doing so can advance a more sustainable future in water resource management and contribute to the protection of public health and the environment.

Most reviews published prior to 2021 emphasized the fundamental mechanisms of electrocoagulation and its conventional applications, but they did not systematically integrate the technological, environmental, and economic advancements that have emerged in the last four years. Unlike earlier works, the present review focuses on recent empirical evidence (2014-2025) and provides a detailed comparative assessment of EC performance across more than 20 industrial sectors, highlighting emerging contaminants—such as nanoplastics, pharmaceutical residues, and endocrine disruptors—that were not widely addressed in earlier reviews. Furthermore, this review synthesizes quantitative data on removal efficiencies, operational parameters, and cost structures using a structured PICO-PRISMA methodology, which ensures a level of rigor and transparency not typically seen in prior reviews. By contrasting multiple reactor configurations, hybrid technologies, and cost ranges, our work provides novel decision-making criteria applicable for industries evaluating the feasibility of EC adoption, thus extending beyond purely descriptive reviews. Another distinctive contribution is the identification of cross-cutting operational challenges, such as electrode degradation dynamics, sludge valorisation opportunities, and scale-up barriers, integrating insights from both laboratory and pilot-scale studies. This approach enables the review to serve as a bridge between academic research and practical industrial implementation, offering a broader and more contemporary perspective than the existing literature.

As part of the conceptual findings derived from the analysis of the studies included in this systematic review, the fundamental mechanisms that explain contaminant removal by electrocoagulation and electrooxidation are identified. These mechanisms enable proper interpretation of the efficiency trends observed across different wastewater matrices.

Mechanisms of electrocoagulation and electrooxidation

Electrocoagulation is an electrochemical process in which coagulants are generated in situ by dissolving sacrificial aluminium or iron electrodes. Under direct current, the released metal ions

(Al^{3+}, Fe^{2+} /Fe^{3+}) hydrolyse to form hydroxide complexes (*e.g.* $Al(OH)_3$, $Fe(OH)_3$) that act as coagulating agents. These mechanisms have been described in recent studies [123,124]. During EC, the oxidation of aluminium and iron at the anode occurs according to the anodic dissolution reactions (Equations (1a) and (1b)), while the corresponding reduction of water takes place at the cathode following Equation (2) [125,126].

Anode (Al):

$$Al \rightarrow Al^{3+} + 3e^- \tag{1a}$$

Anode (Fe):

$$Fe \rightarrow Fe^{2+} + 2e \tag{1b}$$

Cathode (reduction reaction):

$$2H_2O + 2e^- \rightarrow H_2\uparrow + 2OH^- \tag{2}$$

The combination of metal cations and OH^- leads to the formation of metal hydroxides and polymers that neutralize the charge of the colloidal particles, reducing electrostatic repulsion (DLVO) and promoting aggregation via coagulation and flocculation. These flocs also act as adsorbent sponges for dissolved organic matter and heavy metals, trapping both particulate and soluble species through physicochemical mechanisms (adsorption, coprecipitation, entanglement). The simultaneous generation of hydrogen bubbles at the cathode promotes the electroflotation of the flocs, facilitating their separation by surface flotation in appropriate reactor configurations [127].

The efficiency and dominant pathway (adsorption vs. coprecipitation *vs*. electroflotation) depend strongly on operating parameters: current density (or electrical charge per volume), pH (which defines the predominant hydroxy -metallic species), electrical conductivity (presence of auxiliary electrolytes such as NaCl), electrodialysis time, reactor geometry, and electrode arrangement (monopolar/bipolar, parallel, spacing). For example, higher current densities increase the anodic dissolution rate but can also favour secondary reactions (oxygen evolution and active chlorine formation if Cl- is present), thereby modifying the nature of the flocs and byproducts formed. Experimental reports and meta-analyses indicate that the choice between Al and Fe as the anode also affects results: Fe typically yields better BOD_5/COD removal in certain effluents, whereas Al is more effective for turbidity and colour, due to differences in the hydroxy-formed species and in polymerization kinetics [128].

At a finer mechanistic level, the removal of contaminants in electrocoagulation results from several coupled processes. First, charge neutralization and colloidal destabilization occur, whereby the generated metal hydroxides neutralize the surface charges of the particles and promote their aggregation. Simultaneously, adsorption and coprecipitation occur, in which dissolved compounds, both organic and metallic, are adsorbed onto the surfaces of the precipitated hydroxides or incorporated into the solid phase during precipitation. Additionally, electroflotation contributes to the process, since the hydrogen bubbles, and in some cases oxygen bubbles, generated at the electrodes carry the flocs to the surface and facilitate their separation. Finally, in the presence of chloride electrolytes or under high current densities, a parallel electrochemical oxidation can occur in which oxidizing species such as Cl_2, HOCl or reactive radicals capable of degrading organic compounds are generated, which introduces an additional oxidative contribution to the traditional coagulation mechanism [129].

Electrooxidation (EO) (also called anodic oxidation) degrades contaminants by direct oxidation on the anode surface and/or by indirect oxidation using electrogenerated oxidizing species at the electrode/solution interface. The distinction between “active anodes” and “non-active anodes” is central to understanding activation: non-active anodes, such as boron-doped anodes. Diamond (BDD) and lead dioxide (PbO_2) promote the generation of free or adsorbed hydroxyl radicals with high oxidizing activity ($\cdot OH_{ads}$) and a high overpotential for O_2 evolution. Thus, water is oxidized at the surface, forming $\cdot OH$ ions that react almost non-selectively with adjacent organic matter, promoting deep mineralization. In contrast, active anodes (Ti/IrO_2, Ti/RuO_2) tend to favour the formation of surface oxides that mediate electron transfer and produce less reactive and more selective oxidants, with a greater propensity to form intermediates and lower rates of complete mineralization [130].

Typical electro-oxidation mechanisms include, firstly, direct oxidation or the inner-sphere pathway, in which the adsorbed contaminant transfers electrons directly to the anode. This mechanism occurs mainly on surfaces with high adsorption affinity and becomes significant when electron transfer is kinetically favourable. Additionally, hydroxyl radical-mediated oxidation can occur, a pathway in which non-active anodes promote the oxidation of water to generate adsorbed hydroxyl radicals ($\cdot OH_{ads}$) on the anodic surface, according to Equation (3):

$$H_2O \rightarrow \cdot OH_{ads} + H^+ + e^- \quad (3)$$

The $\cdot OH_{ads}$ react with adjacent organic matter forming intermediates and, eventually, CO_2 and H_2O; this route usually exhibits high mineralization efficiency in BDD and PbO_2 [131].

Indirect oxidation by electrogeneration of stable oxidants occurs when inorganic species Cl^-, Br^-, SO_4^{2-} are present. Electrochemical oxidation (EO) can generate significant secondary oxidants, *e.g.* $Cl_2/HOCl/ClO^-$ in the presence of chlorides, or persulphates/sulphate radicals in the presence of sulphates, that act throughout the volume and attack dissolved compounds far from the anodic interface. The formation of these oxidants depends on the ionic composition and applied potential; for example, the oxidation of Cl^- produces Cl_2, which in water forms $HOCl/ClO^-$ (pH-dependent), species that participate in disinfection and indirect oxidation [130].

Activation, the conditions under which each pathway predominates, is controlled by the applied potential (and therefore current density), the nature of the anode (BDD *vs.* Ti/ IrO_2), the electrolyte composition (presence of Cl^-, HCO_3^-, SO_4^{2-}), pH, and temperature. Recent experimental studies recommend determining the "overpotential window" in which $\cdot OH$ generation is maximal (through voltammetry/Tafel currents and radical scavenging assays) for each anode and electrolyte; this procedure allows the selection of operating conditions that maximize HORS (highly oxidizing reactive species) and minimize parasitic reactions (O_2 evolution, formation of halogenated byproducts) [131].

The experimental characterization that distinguishes pathways includes measurement of oxidation products (TOC/CO_2, intermediates), detection of radicals by trapping and EPR techniques, analysis of free chlorine and halogenated species (when Cl^- is present), and electrochemical studies (CV, LSV, EIS) that define the oxidant generation region. Recent work with BDD and other advanced materials shows that controlled anode “activation” (pretreatment/conditioning, working potential) is crucial for optimizing selectivity towards mineralization versus the formation of halogenated byproducts; therefore, activation and electrochemical characterization protocols should be reported in detail in applied studies [132].

Industrial uses of electrocoagulation

Electrocoagulation (EC) has become established as a mature, versatile, and effective technology for treating real-world industrial wastewater, demonstrating its ability to remove complex contaminants, organic matter, metals, suspended solids, colour, fats, proteins, nutrients, and nanoplastics under robust operating conditions. Most of the reviewed studies used real-world effluents, confirming the practical relevance of this technology in various production sectors.

In aquaculture, EC has been applied directly to real-world effluents with high organic loads, demonstrating significant removals of turbidity and contaminants using hybrid iron-aluminium electrodes [17]. In the palm oil industry, the integration of bipolar electrocoagulation with ultrafiltration has been successfully tested on real-world POME [19], and its operation with photovoltaic solar energy has also been evaluated at a practical scale [77]. Tannery effluents, characterized by high concentrations of COD, chromium, and solids, have been extensively studied under real-world conditions using traditional EC [73], EC combined with UV [74], and processes optimized for complex matrices [83].

Electrochemical coagulation (EC) has also demonstrated high efficiency in real dairy-industry wastewater, achieving significant reductions in fat, solids, and organic load using zinc and aluminium electrodes [76,81,89,93], and has been used in mixed dairy-meat effluents [87]. In this sector, innovative solutions, such as repurposing beverage cans as electrodes, have even been explored [75]. Similarly, in the textile industry, EC has demonstrated superior efficiency compared with chemical coagulation in removing dyes and solids from real effluents [78]. Other industrial processes have integrated EC with electrooxidation to treat highly contaminated water, such as in the washing of industrial containers [84].

Additionally, multiple industries have reported solid results under real-world conditions, such as the paper industry using EC with iron electrodes [90], cattle slaughterhouses through batch and continuous trials that validate its economic viability [91], and poultry farms, where the EC-peroxidation combination improves the removal of recalcitrant compounds [92]. EC has also been applied to the removal of insecticides from industrial effluents [94] and to recirculation configurations to optimize operating parameters across various real-world industrial matrices [79].

According to the reviewed documents, only 20 researchers explicitly used synthetic wastewater in their studies, primarily for methodological purposes to analyse specific mechanisms or isolate electrochemical variables. Representative examples include research on nanoplastics in synthetic water [85] and certain comparative studies on synthetic milky water that sought to evaluate parametric influences in a controlled manner [94]. These approaches are useful for understanding fundamental phenomena, but they constitute a small fraction of the total research analysed.

Taken together, the overwhelming predominance of studies using real industrial wastewater, from tanneries [74,83], dairies [75,76,81,89,93], slaughterhouses and poultry farms [87,91,92], paper mills [90], pig farms [82], textile mills [78], aquaculture [17], and palm oil processing [19], demonstrates that electrocoagulation is not a technique limited to synthetic systems or laboratory tests, but rather a process applied operationally to achieve substantial reductions in COD, BOD_5, turbidity, colour, oils and greases, metals, and other complex contaminants. This consolidated evidence reinforces the viability and industrial relevance of EC as a robust solution for treating real-world effluents in multiple production sectors.

Comparative analysis with previous research

The comparative analysis with previous reviews (Table 6) reveals that the literature on electrocoagulation (EC) exhibits marked thematic fragmentation, which limits an integrated understanding of the process and its industrial applicability. Each prior study has examined specific dimensions (mechanistic, sectoral, or technological), but none has articulated these perspectives in a cross-cutting manner. In this context, the present work makes a substantial contribution by integrating, systematizing, and comparing diverse evidence using a rigorous PRISMA methodology and clearly defined PICO criteria.

Comprehensive reviews, such as that by Jing *et al.* [61], have demonstrated the versatility of ecological efficiency (EC) across various industrial sectors; however, their scope remains primarily descriptive and lacks a standardized analysis that would enable comparison of results across industries. The exclusive reliance on operational parameters and conventional treatment indicators leaves critical issues, such as costs, sustainability, and technological barriers to adoption, unresolved. In contrast, this review addresses these dimensions as central elements, enabling the evaluation of EC performance from an industrial decision-making perspective.

Table 6. *Comparison of previous reviews on electrocoagulation and contributions of the present study*

Main focus	Types of effluents analysed	Variables evaluated	Limitations identified by previous authors	Novel contributions of the current study	Study / review
Use of electrocoagulati on (EC) in industrial wastewater	Effluents: textile, mining, petrochemical, tannery, pharmaceutical, food-related, and mixed effluents	EC mechanisms, operating parameters (pH, current density, electrode spacing, time)	Lack of industrial-scale studies; limited cost data; heterogeneous results	This study applies PRISMA methodology; classifies and compares 51 studies, including cost analysis and technological barriers	[61]
Electrochemical mechanisms	Synthetic, domestic, and industrial	Floc formation, reaction pathways	Limited discussion applied to real industries	The current review analyses real efficiency by industrial sector	[40]
Diverse industrial effluents	Mining, food, textiles	Operating conditions	Limited comparison with alternative treatment methods	This study compares EC vs chemical treatments, electro-Fenton, and advanced oxidation processes	[50]
Hybrid EC-EO-UF systems	Various	Technological integration	Does not evaluate costs or implementation barriers	The current study includes real-world barriers related to use, costs, and sustainability	[24]
Current general overview	Various effluents	Technological advances	No analysis of knowledge gaps	The current review identifies research gaps (industrial scale, sludge, costs)	[47]
Hybrid processes	Oils and greases	Efficiency, integration	Does not compare with conventional treatments	Your study compares EC against both classical and advanced treatments	[26]
EC in textiles	Textile	Colour, turbidity	Limited to a single sector	Your study covers more than 12 industrial sectors	[52]

On the other hand, more specialized works, such as those by Das *et al.* [40] and Shahedi *et al*. [50], examine operational mechanisms and conditions but do so from sectoral or laboratory perspectives that limit the generalizability of results. The current review overcomes this limitation by incorporating studies from more than a dozen industries, allowing the identification of performance patterns and common challenges that do not emerge in reviews focused on isolated matrices.

In the field of hybrid technologies, studies by Ammar *et al.* [24] and Asfaha *et al.* [26] demonstrate the potential of integrating electrowinning (EC) with advanced oxidation or separation processes. However, these studies focus on the technical operation of the systems, without assessing their economic viability or scalability. This analysis moves in that direction by including criteria such as sustainability, operating costs, electrode wear, and sludge management, providing a more comprehensive evaluation of the actual feasibility of these technologies in industrial contexts.

Furthermore, recent general reviews, such as that of Boinpally *et al.* [47], identify technological advances but offer little discussion of knowledge gaps or methodological heterogeneity in existing studies. The current review addresses this deficiency by explicitly synthesizing persistent gaps: the absence of industrial pilot studies, the lack of life cycle assessments, the scarcity of standardized reporting criteria, and the need for comprehensive sludge management strategies.

Even sector-specific reviews, such as that of Sen *et al.* [52], which focus on textile applications, highlight the need for multi-industry assessments. The present study addresses this need by comparing 51 research studies from various production sectors, enabling a cross-sectional characterization of EC behaviour with matrices containing substantially different organic, inorganic, and emergent fillers.

Taken together, this analysis demonstrates that the present study not only synthesizes existing information but also critically reorganizes it within a robust and comparative methodological framework. By integrating multiple sectors, alternative technologies, economic variables, and technical barriers, this review provides a comprehensive perspective that surpasses the fragmented approaches of previous studies. It thus establishes itself as a novel and necessary contribution to guiding the development and industrial implementation of electrocoagulation.

Conclusions

This systematic review on the application of electrocoagulation in industrial wastewater treatment has revealed significant findings that highlight its effectiveness and potential for pollutant management. This technology is presented as highly efficient for the removal of various pollutants, including heavy metals, oils, and suspended solids, achieving superior removal rates compared to traditional methods, such as chemical coagulation, in addition to offering advantages such as reduced sludge generation and the possibility of reusing treated water. Critical operational factors were identified, such as pH, applied electrical current, and treatment time, which must be carefully controlled to maximize process effectiveness. The importance of proper electrode selection was also emphasized, as different materials can affect treatment efficiency. However, significant barriers to its implementation were encountered, such as high initial installation and operating costs, as well as a lack of technical knowledge and training in the use of this technology, which can hinder its widespread adoption despite its evident benefits. Electrocoagulation is presented as a promising solution for industrial wastewater treatment, offering an effective and sustainable alternative to conventional methods. It is essential to promote additional research on process optimization and long-term cost assessment, as well as prioritize the training of professionals in the field and foster collaboration between academia and industry, to maximize its positive impact on wastewater management and advance toward a more sustainable future in water resource management. Furthermore, research into the integration of technologies, conducting life cycle analyses that assess the environmental impact compared to other methods, and developing prototypes that allow observation of electrocoagulation performance under real-world conditions are suggested.

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