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INVESTIGACIÓN

Electrocoagulation as an Emerging Technology for Wastewater Treatment in Different Industries: A Review

Electrocoagulación como tecnología emergente al tratamiento de las aguas residuales en distintas industrias: una revisión

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Abstract

The electrocoagulation (EC) technique has been considered a popular treatment alternative for the effective separation of organic and inorganic contaminants. This technique generates coagulating particles *in situ* through the electrolysis of a sacrificial anode that destabilizes suspended, dissolved, or emulsified contaminants in a liquid medium by inducing an electric field. EC has been widely studied due to its versatility, ease of installation, lower cost, and for being an environmentally friendly technology. For this article, a search and information-gathering phase was conducted in which Scopus, ScienceDirect, and Google Scholar were identified as the necessary tools for locating information on the electrocoagulation process as a wastewater treatment in various industries. This paper reviews studies on advances in EC applied to different types of industrial wastewater, focusing on evaluating the operating variables and optimal treatment conditions that are vital to the process. Likewise, the effect of the electrocoagulation on the quality properties of wastewater from different sectors is examined, considering factors such as current density, pH, reactor geometry, treatment time, and electrode spacing.

Objective: To determine the effect of the electrocoagulation process on the quality properties of wastewater from various industries as a function of physicochemical and geometric parameters.

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Methodology: A search and information-gathering phase was carried out using Scopus, Sciencedirect, and Google Scholar as the main sources. Subsequently, a scientific monitoring study was conducted following a methodology structured in four stages: planning, research, analysis, and competitive intelligence. Additionally, a literature review was conducted to identify needs and select keywords focused on the electrocoagulation process as a wastewater treatment technology in various industries.

Results: The review revealed that wastewater treatment removal efficiency is achieved by removing one or more of its components in whole or in part, depending on the initial or inlet organic load. The main parameters evaluated were Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), Total Suspended Solids (TSS), color, turbidity, Total Organic Carbon (TOC), and oil and grease content. Several studies have concluded that, under optimal treatment conditions, electrocoagulation can achieve approximately 90% removal of the pollutant loads in wastewater from diverse industrial sectors.

Conclusions: The review showed that electrocoagulation technology is a highly effective alternative for treating a wide variety of industrial effluents containing pollutants that cannot be effectively removed by conventional treatment methods. In addition, more research is needed to study the impact of new organic coagulant-assisted processes, reactor designs, electrode configuration, electrocoagulation mechanisms, processing conditions and electrode dissolution phenomena, in order to obtain greater removal and improvement in the treatment process.

Financing: The project was financed through the National Fund for Science, Technology, and Innovation of the General System of Royalties (Bank of National Investment Programs and Projects), the University of Sucre and the PADES group, within the framework of the project "Technological strengthening of the Colombian Caribbean region through the development of transformation processes of starchy raw materials (cassava, yams and sweet potatoes) in the department of Sucre", identified with the BPIN code 2020000100035.

***Keywords*:** Wastewater, electrocoagulation, quality properties, operating parameters, optimal conditions, electrocoagulation systems.

Resumen

La técnica de electrocoagulación (EC) se ha considerado una alternativa popular de tratamiento para la separación eficaz de contaminantes orgánicos e inorgánicos. Está técnica genera partículas coagulantes in situ mediante la electrolisis de un ánodo de sacrificio que desestabiliza los contaminantes suspendidos, disueltos o emulsionados en un medio líquido mediante la inducción de un campo eléctrico. La EC ha sido estudiada ampliamente debido a su versatilidad, facilidad de instalación, menor costo y por ser una tecnología amigable con el medio ambiente. Para la elaboración de este documento se realizó una fase de búsqueda y captación de información, en la cual se identificaron las herramientas de Scopus, Sciencedirect y Google Scholar como las herramientas necesarias para la búsqueda de información sobre el proceso de electrocoagulación como tecnología de tratamiento de aguas residuales en diversas industrias. En este documento, se han revisado estudios sobre los avances de la EC en varios tipos de aguas residuales en distintas industrias donde se han evaluado las variables operativas y condiciones óptimas de tratamiento que son vitales para el proceso de electrocoagulación. Asimismo, se establece el efecto del proceso de electrocoagulación sobre las propiedades de calidad de aguas residuales de las diferentes industrias, teniendo en cuenta los diversos parámetros que afectan al sistema, como densidad de corriente, el pH, la geometría del reactor, el tiempo de tratamiento y distancia entre los electrodos.

Objetivo: conocer el efecto del proceso de electrocoagulación sobre las propiedades de calidad de aguas residuales provenientes de diversas industrias en función de parámetros fisicoquímicos y geométricos.

Métodología: se realizó una fase de búsqueda y captación de información, en la cual se identificaron las bases de dato Scopus, Sciencedirect y Google Scholar como las principales fuentes para la búsqueda de información. Posteriormente, se realizó una revisión bibliográfica para identificar necesidades y seleccionar palabras claves enfocadas al proceso de electrocoagulación como tecnología de tratamiento de aguas residuales en diversas industrias.

Resultados: durante la revisión, se encontró que la eficiencia de eliminación del tratamiento de aguas residuales se logra eliminando uno o más de sus componentes en su totalidad o en parte, en función de la carga orgánica inicial o, de entrada. Los principales parámetros evaluados fueron Demanda Química de Oxígeno (DQO), Demanda Bioquímica de Oxígeno (DBO), sólidos suspendidos totales (SST), color, turbidez, carbono orgánico total (COT), contenido de aceite y grasa. Lo que llevó a que varios estudios concluyeran que en condiciones óptimas de tratamiento se logra una remoción efectiva de aproximadamente el 90% de la carga contaminante de las aguas residuales en diversas industrias.

Conclusiones: la revisión demostró que la tecnología de electrocoagulación ha sido una gran alternativa aplicada con éxito para el tratamiento de una amplia variedad de efluentes industriales que contienen contaminantes, los cuales no pueden ser eliminados de manera efectiva mediante métodos de tratamiento convencionales. Se evidenció también la necesidad de abarcar más investigaciones para estudiar el impacto de los nuevos procesos asistidos con coagulantes orgánicos, diseños de reactores, configuración de los electrodos, los mecanismos de electrocoagulación, las condiciones de procesamiento y los fenómenos de disolución de los electrodos, con el propósito de obtener una mayor eliminación y mejora en el proceso de tratamiento.

Financiamiento: el proyecto fue financiado a través del Fondo Nacional de Ciencia, Tecnología e Innovación del Sistema General de Regalías (Banco de Programas y Proyectos de Inversión Nacional), la Universidad de Sucre y el grupo PADES en el marco del proyecto "Fortalecimiento tecnológico de la región Caribe colombiana a través del desarrollo de procesos de transformación de materias primas amiláceas (yuca, ñame y batata) en el departamento de Sucre", identificado con el código BPIN 2020000100035.

***Palabras clave*:** Aguas residuales, electrocoagulación, propiedades de calidad, parámetros operativos, condiciones óptimas, sistemas de electrocoagulación.

INTRODUCCIÓN

Electrocoagulation (EC) is defined as a process that destabilizes suspended and dissolved substances in a liquid medium by inducing an electric field in the effluent. This technology has been widely applied for the treatment of wastewater containing high loads of organic and inorganic pollutants, generating coagulants and hydroxides that destabilize suspended particles or absorb dissolved contaminants [1]. The technique mainly involves applying of an electric current to gradually dissolve a sacrificial anode during the reaction, thus producing a large number of highly charged metal cations *in situ*. These cations act as coagulants and are hydrolyzed near the anode to form M(OH)n hydroxides, while water is reduced to H_2 at the cathode. The resulting hydrogen bubbles promote floc formation, enabling contaminants to be removed through both precipitation and flotation [2].

The electrocoagulation process offers several advantages, including simple, easy-to-operate equipment, reduced sludge production, and the absence of added chemical reagents, which minimizes the risk of secondary pollution. The gas bubbles generated during electrolysis carry contaminants to the surface, facilitating their separation and collection. In addition, EC systems require minimal maintenance due to the controlled electrical potential and absence of moving parts, and they can be powered by renewable energy sources such as solar or wind [1]. Over recent decades, EC has been extensively studied as an effective technology for the treatment of various types of wastewater, enabling the removal of non-metallic inorganic species, heavy metals, organic pollutants, oils, greases, and real industrial effluents [3].

Electrocoagulation can be operated in either batch or continuous systems, depending on the type and concentration of contaminants. According to [4], the selection of reactor configuration depends on factors such as pollutant properties, effluent volume, application type, treatment time, current density, and operating conditions. Batch reactors are more suitable for laboratory and pilot-scale studies due to their smaller working volume, whereas continuous systems are preferred for large-scale industrial applications [21]. An EC reactor typically consists of an electrolytic cell equipped with sacrificial metal electrodes, commonly iron (Fe) or aluminum (Al), connected to a power source. The anodes and cathodes may be of the same or different materials [6]. Fe and Al plates are most commonly used because they are inexpensive, readily available, and highly efficient for pollutant removal [7].

In the food sector, particularly in the sugar industry, batch-type EC systems incorporating Fe, Al, and Cu electrodes have achieved removal efficiencies of up to 97% Similarly, studies in the dairy and meat industries using Fe electrodes in batch systems have reported pollutant removal rates above 90% [8]. In the textile industry, [9] implemented discontinuous EC systems with Al and Fe electrodes, achieving contaminant removal efficiencies above 80%. Likewise, [10] used stainless-steel electrodes in similar batch systems, reaching efficiencies of approximately 81%. Furthermore, [7] evaluated batch EC systems in the oil refinery industry using Al electrodes and obtained removal efficiencies close to 90%, while [11] reported comparable results using stainless-steel and Al electrodes. Altogether, these studies confirm that EC performance is strongly influenced by several parameters, including electrode material and configuration, applied current, treatment time, inter-electrode distance, current density, pH, and temperature [12].

Recent efforts have focused on optimizing EC reactor design to enhance pollutant removal rates and energy efficiency [13]. One of the main areas of technological development involves improving control over operational and influential variables, which determine the overall dynamics of the EC process [14]. [15] compared two EC reactor configurations for arsenic removal from groundwater in terms of efficiency and operating costs. The first reactor was air-fed and consisted of a round-bottomed base unit (150 mm in diameter, 45 mm thick) with several 2 mm holes, and a cylindrical titanium cathode perforated with 5 mm holes at 10 mm intervals. The second system was a batch reactor with vertically placed Fe plate electrodes (50–73 mm), where two anodes and two cathodes were connected in monopolar-parallel mode. The first configuration achieved 99.3% arsenic removal at an operating cost of $\$1.55/m^3$, while the second achieved 96.9% removal at only $\$0.10/m^3$.

To date, most research has explored hybrid EC systems that integrate other advanced technologies to enhance pollutant removal capacity and treatment performance [16]. Other studies, such as [17], have focused on electrode reactions and pollutant removal mechanisms, including kinetic models, adsorption isotherms, and efficiency analysis. Similarly, [7] investigated EC performance across different wastewater types, in order to evaluate operational variables and comparing EC with conventional chemical coagulation, since these parameters largely govern removal mechanisms. Nonetheless, significant knowledge gaps remain regarding the effects of electrocoagulation on the physicochemical quality of wastewater from agro-industrial processes. Therefore, this review aims to assess the impact of the electrocoagulation process on the quality parameters of wastewater from various industries, as influenced by physicochemical and geometrical operating conditions.

Principles of electrocoagulation

Electrocoagulation is a process that removes pollutant loads from wastewater by applying an electric current using electrodes (anode and cathode), which can be made of the same or different materials (Al–Al, Fe–Fe, Al–Fe, Fe–Al). During electrolysis, the anode material undergoes oxidation, generating metallic ions such as Al^{3+} or Fe^{2+}/Fe^{3+}, depending on the electrode used. These cations act as *in situ* coagulants, promoting the formation of aluminum and iron hydroxides ($Al(OH)_3$, $Fe(OH)_2$, $Fe(OH)_3$) which facilitate the aggregation and removal of pollutants [18], [19]. Simultaneously, the hydrogen gas produced at the cathode aids in contaminant flotation, bringing them to the surface as floating sludge [6], [20].

Electrodes in EC systems may be arranged in either monopolar (MP) or bipolar (BP) configurations [21]. The MP configuration can consist of electrodes connected in parallel (MP-P) or in series (MP-S) arrangements [21]. In the MP–P configuration (Fig. 1A), under direct current (DC) conditions, the electrodes are alternately connected so that the current flow is evenly distributed across the entire electrode array [19]. Conversely, in the MP–S configuration (Fig. 1B), only the two external electrodes (anode and cathode) are connected to the power supply, with no interconnection to the internal electrode pairs [18]. These internal electrodes, often referred to as sacrificial electrodes, help reduce anode dissolution and cathode passivation [13].

In the BP configuration (Fig. 1C), the external electrodes are connected to the power supply, whereas the internal (sacrificial) electrodes remain electrically unconnected [19]. As a result, the array contains both bipolar (internal) and monopolar (external) electrodes, and the system operates in a series connection mode [18]. By contrast, in bipolar parallel (BP–P) configurations, the sacrificial electrodes are alternated between two parallel plates that are not directly connected to the power source [5].

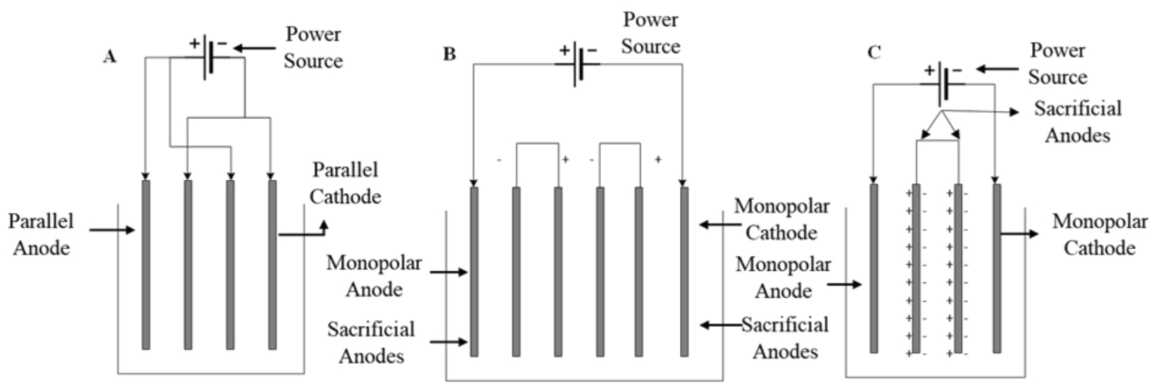

Figure 1. *EC reactor with different electrode arrangements at discontinuous scale: (A) Monopolar parallel connection (MP-P); (B) Monopolar series connection (MP-S); (C) Bipolar series connection (BP-S).*

Note. **Source:** Adapted from [18].

Electrocoagulation systems

The systems used in the electrocoagulation process play a crucial role in determining the removal efficiency of organic and inorganic loads present in industrial effluents. Several factors must be considered, including cell design, reactor type, electrode configuration, electrode material, plate thickness, and the distance between electrodes [22]. It should be emphasized that the electrode configuration is one of the most critical parameters for achieving higher removal efficiencies in EC systems [23]. The electrocoagulation process generally occurs in several stages: (I) generation of metal cations in the system; (II) formation of hydroxyl ions through the cathodic hydrolysis process; (III) interaction between metal cations and hydroxyl ions to form metal hydroxides; (IV) oxidation of toxic contaminants in to less toxic species; (V) neutralization of contaminants by metal hydroxides; (VI) contaminant removal by sweep coagulation; and (VII) flotation of the formed flocs to the surface assisted by hydrogen gas generated at the cathode [6].

In EC, contaminant removal primarily occurs through adsorption, coagulation, and flotation mechanisms [7]. During anodic dissolution, coagulant species (metal ions) are produced *in situ* (Equation 1), accompanied by the generation of hydroxyl ions (Equation 3) and hydrogen gas at the cathode (Equation 2). These coagulants facilitate the formation of flocs composed of metal hydroxides, which act as effective adsorbents for contaminant removal [20]. Furthermore, the hydrogen gas produced at the cathode aids in lifting these flocs to the water surface, forming a layer of floating sludge [24].

At the anode:

$$M_{(s)} \rightarrow M^{n+}_{(aq)} + ne^- \quad (1)$$

$$H_2O \rightarrow 4H^+_{(aq)} + O_{2(g)} + 4e^- \quad (2)$$

At the cathode:

$$nH_2O + ne^- \rightarrow (^n/_2)\ H_{2(g)} + nOH^-{}_{(aq)} \tag{3}$$

Reactions for Al electrodes

When aluminum (Al) is used as the electrode material, cationic monomeric species such as Al^{3+} and $Al(OH)^{2+}$ (Equation 4) are generated at low pH. At optimal pH conditions, these species are transformed into $Al(OH)_3$ (Equation 5), which can subsequently polymerize to form $Al_n(OH)_{3n}$ (Equation 6) [18].

$$All_{(s)} \rightarrow Al\,_{(\ aq}^{\ 3}{}^{+)} + 3_e{}^- \tag{4}$$

$$Al3^+{}_{(aq)} + 3H_2O_{(l)} \rightarrow Al(OH)_{3(s)} + 3H^+_{(\ aq)} \tag{5}$$

$$nAl(OH)_3 \rightarrow Aln(OH)_{3n} \tag{6}$$

Reactions for Fe electrodes

When iron (Fe) is used as the electrode material, oxidation reactions at the anode lead to the formation of iron hydroxides, $Fe(OH)_n$ ($n = 2$ or 3). Two main reaction systems are recognized: the first leading to $Fe(OH)_3$ formation and the second to $Fe(OH)_2$ [18].

System 1:

Anode:

$$4Fe_{(S)} \rightarrow 4Fe\,_{(\ aq}^{\ 2}{}^{+)} + 8e^- \tag{7}$$

$$4Fe\,_{(\ aq}^{\ 2}{}^{+)} + 10H_2O_{(l)} + O_{2(g)} \rightarrow 4Fe(OH)_{3(S)} + 8H^+_{(\ aq)} \tag{8}$$

Cathode:

$$8H^+_{(\ aq)} + 8e^- \rightarrow 4H_{2(g)} \tag{9}$$

General:

$$4Fe_{(s)} + 10H_2O_{(l)} + O_{2(g)} \rightarrow 4Fe(OH)_{3(s)} + 4H_{2(g)} \tag{10}$$

System 2:

Anode:

$$Fe_{(s)} \rightarrow Fe\,_{(\ aq}^{\ 2}{}^{+)} + 2_e{}^- \tag{11}$$

$$Fe\,_{(\ aq}^{\ 2}{}^{+)} + 2OH^-_{(\ aq)} \rightarrow Fe(OH)_{2(S)} \tag{12}$$

Cathode:

$$2H_2O_{(l)} + 2_e^{-} \rightarrow H_{2(g)} + 2OH^{-}_{(\ aq)} \tag{13}$$

General:

$$Fe_{(s)} + 2H_2O_{(l)} \rightarrow Fe(OH)_{2(s)} + H_{2(g)} \tag{14}$$

It is important to note that several operating parameters significantly influence the efficiency of the electrocoagulation process: (1) initial pH: affects current efficiency and the rate of metal dissolution to form hydroxides. It also varies during electrolysis depending on electrode material and initial water chemistry; (2) electrocoagulation time: determines the extent of anodic dissolution and coagulant release; therefore, treatment efficiency depends on the concentration of metal ions produced; (3) distance between electrodes: as the distance increases, resistance between electrodes rises, reducing ion transport and hydroxide formation; (4) current density: higher current densities increase ion generation but can also cause excessive heating, reducing treatment efficiency; (5) type and concentration of the electrolyte: higher electrolyte concentrations increase conductivity and decrease resistance, directly enhancing removal efficiency. Conductivity itself depends on the total concentration of dissolved solids [1], [25], [26].

Use of the electrocoagulation process in different industries.

Wastewater generated by the food industry is characterized by high concentrations of Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD), as well as elevated levels of fats, oils, and grease. According to [8], a batch-type electrocoagulation system was employed, consisting of a rectangular acrylic reactor with an approximate capacity of 12 L (Fig. 2A). Depending on the experimental design, the variables considered were the number of electrodes and treatment time, with electrode configurations of 3, 6, and 13 units. Iron and aluminum were used as electrode materials, arranged side by side with an interelectrode distance of 20 mm. At the same time, the electrodes were connected to a direct current (DC) power source with a voltage range of 0–60 V and a maximum output of 30 A (Fig. 2A). A working voltage of 12 V was selected to protect the power supply and prevent accidents during operation, since higher currents could exceed the limits permitted by the equipment (Fig. 2B). The results demonstrated an effective pollutant removal performance, achieving rates above 95 %.

Regarding the types of systems used by these authors [8], it can be stated that batch electrocoagulation reactors, when operated under optimal conditions, significantly improve water quality due to their efficiency in removing organic loads and pollutants. Their main advantage lies in their operational flexibility, making them particularly suitable for industries that handle variable production processes. This adaptability allows implementation without requiring new facilities or substantial structural modifications [8].

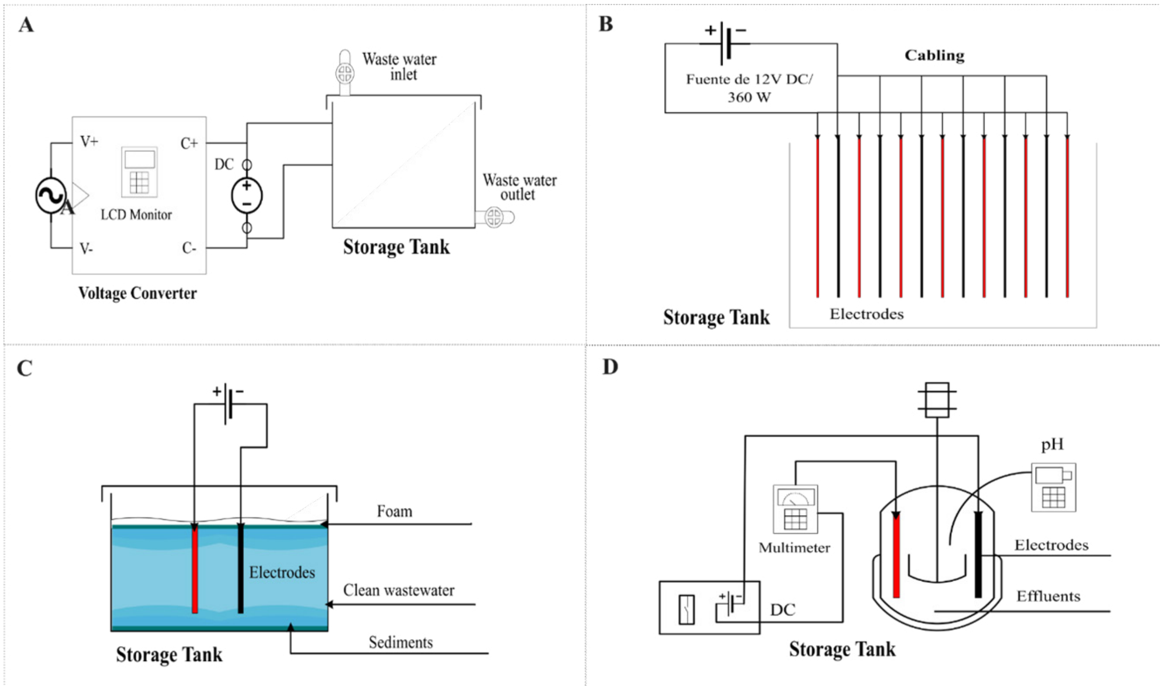

Figure 2. *Electrocoagulation systems used in different industries: (A) Batch-type electrocoagulator assembly with monopolar electrodes connected in parallel; (B) Connection configuration of the iron electrodes; (C) Treatment of rubber waste by the electrocoagulation method; (D) Schematic diagram of the assembly.*

Note. **Source:** Adopted from [8], [11], [27].

In the rubber industry, [27] employed a batch-type electrocoagulation system equipped with aluminum and stainless-steel electrodes, regulator units, digital multimeters, and anode–cathode connection cables. The experimental setup allowed the variation of both processing time and electrode material. The electrodes measured 11 cm × 11 cm, with a spacing of 1 cm between them. Voltage varied between 12 and 18 V, with treatment durations of 30, 60, 90, 120, and 150 minutes. Under these conditions, pollutant removal efficiencies of approximately 85 % were achieved. The waste treatment equipment used in this study is shown in Fig. 2C.

In the textile industry, [10] set a cylindrical electrolytic reactor made of acrylic, with dimensions of 60.0 cm in height and 10.0 cm in diameter (Fig. 2D). Stainless-steel plate electrodes were connected in a bipolar series configuration. Power consumption was monitored using a wattmeter and a voltage source of 13.8 V. 20 A was applied through an electrical circuit capable of generating current pulses between 0 and 2,200 Hz. This system achieved pollutant removal efficiencies that exceeded 85 %.

Reference [28] employed a plate-electrode reactor to treat laundry industry wastewater (LWW). Optimization of the treatment considered parameters such as electrolysis time, pH, and current density, with experiments performed in batch mode (Fig. 3A). The reactor contained seven electrodes (four anodes and three cathodes), with an effective anodic surface area of 350 cm² per side and an interelectrode distance of 10 mm. Under these conditions, an organic load removal efficiency of approximately 87 % was obtained.

Similarly, in oil refinery industries, [29] applied an electrocoagulation system based on a monopolar cylindrical batch reactor made of Pyrex glass, measuring 25 cm in height and 14 cm in diameter. The cathode was made of stainless steel and the anode of aluminum, each measuring 15.0 cm × 7.2 cm × 3 mm thick. Direct current was supplied by a DC power source operating between 0 and 30 V with a maximum of 5 A. The experimental setup also included a magnetic stirrer to ensure proper mixing. The treatment achieved removal efficiencies close to 90 %. A schematic representation of the reactor configuration is shown in Fig. 3B.

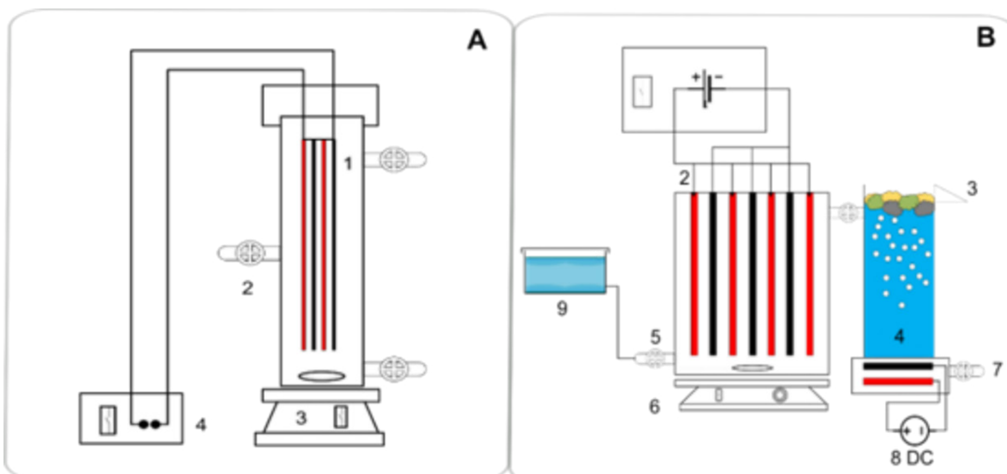

Figure 3. *A) Experimental scheme of the electrocoagulation system: 1: Set of electrodes; 2: collection tap; 3: magnetic stirrer; 4: electrical voltage source. B) Combined electrocoagulation (EC) and electroflotation (EF) treatment system at laboratory scale: 1-DC power for the EC cell; 2-Cell EC; 3-Floating link; 4-FE cell; 5-AR inlet; 6-Magnetic-stirring bar; 7- Purified Ar output; 8- DC for EF cell; 9-Feed sludge tank.*

Note. **Source:** Adopted from [10], [28]

This review highlights that, for wastewater treatment in oil refinery industries, the electrocoagulation technique offers distinct advantages over traditional chemical coagulation methods. These include lower sludge production, reduced chemical consumption, and consequently, lower operational costs. Moreover, optimization of parameters such as cell voltage and solution pH can lead to notable reductions in energy consumption while enhancing pollutant removal efficiency. The use of specially engineered aluminum alloys and the periodic alternation of anode and cathode roles have also been reported to delay electrode passivation, thereby improving system durability and performance [10].

METHODOLOGY

The search for information in the scientific surveillance study was established using the methodology proposed by [30], which is structured into four (4) stages: planning, research, analysis, and competitive intelligence: the different stages of the surveillance study are described below:

Planning: The planning stage began with the definition of the main topic being "Implementation of emerging technologies in the treatment of industrial wastewater" being delimited by "Electrocoagulation". First, a log was created based on a previous bibliographic review to establish key words related to the subject. Having this, it was necessary to validate the words found in order to obtain the search matrix, which was composed of three keywords or expressions combined with three Boolean operators AND, OR, and AND NOT.

Search: After developing the search matrix, information was retrieved from the digital platform Scopus and PatentInspitation, allowing to verify and analyze the results, offering an overview of the scientific and technological production across different areas of science. The search was limited to the period from 2016 to 2022.

Information analysis: the Scopus tool made it possible to identify trends and establish correlations with the subject matter or the general search matrix. Likewise, the VOSviewer tool was used to identify correlations and research prospects, refining the information obtained from Scopus and retaining only the keywords most closely related to the topic. Once this is done, several clusters associated directly and indirectly with the search are created.

Competitive intelligence: Finally, a validation of the data obtained was carried out, through which trends were identified in different areas such as the use of the electrocoagulation process and the potential validation of these emerging technologies at the industrial level. In addition, it was possible to identify future projections in the use of assisted systems as advanced processes for wastewater treatment in various industries.

RESULTS AND DISCUSSION

Effect of electrocoagulation systems on the quality of liquid effluents produced in different industries.

Removal efficiency: The removal efficiency in wastewater treatment is defined in relation to the initial pollutant load and it is typically expressed based on the total or partial separation of one or more of its components. Among the typical parameters evaluated are COD, BOD, TSS, color, turbidity, TOC, and oil and grease content. In their study on wastewater in the rubber industry, the authors of [27] reported that the implementation of an electrocoagulation system using aluminum and stainless-steel electrodes effectively reduced pollutants in wastewater samples. This was evidenced by reductions in TSS, COD, BOD, and NH_3 under conditions of 18 V and 150 min (Table 1). Likewise, [8] demonstrated in the food industry that optimal EC conditions for contaminant removal from dairy and meat wastewater involved the use of 13 iron electrodes, a current density corresponding to 12 V, and a treatment time of 60 min, which achieved approximately 90% removal of total COD, soluble COD, and turbidity. Other authors working in the food sector obtained comparable results, with removal efficiencies exceeding 90%, employing mild steel electrodes arranged in a parallel configuration, spaced 2 cm apart, and a treatment time of 60 min [31]. However, [32] reported slightly lower removal efficiencies, around 85%, using aluminum electrodes with 6–12 plates, an electric potential between 6–12 V, and reaction times of 30–60 min.

In the textile industry, [9] applied aluminum and iron electrodes under conditions of pH 8, a treatment time of 80 min, a current density of 20 A/m², and an electrode spacing of 3 cm. Their results showed high efficiency in contaminant removal, measured through COD and color reduction, leading to significant improvement in wastewater quality. For their part, [10] obtained similar results, achieving nearly 85% removal efficiency by using stainless-steel electrodes under conditions of constant agitation at 200 rpm, a pulse frequency of 1.0 Hz, electrode spacing of 1 mm, and a reaction time of 50 min.

On the other hand, in the electroplating industry, several studies have shown that under conditions of pH 9 and a current density of 2 mA/cm², close to 90% heavy metal removals can be achieved. This efficiency strongly depends on the current density, as higher current levels enhance metal removal [33]. However, [29] in electrocoagulation studies for oil refineries obtained higher removal values than those obtained by Kim *et al.,* (2020), which were above 90 %. These results conducted under optimal conditions of pH 6, DC current of 35 mA/cm², a treatment time of 120 min, and the use of aluminum and stainless-steel electrodes. Such performance is likely influenced by factors such as electrode type, spacing, dimensions, and applied voltage. In a recent study on wastewater treatment from the cardboard industry, [34] it was shown that, under optimal conditions of pH 6.62, an electric current of 10 A and a KCl concentration of 0.5 mol/L, removal efficiencies greater than 90% were achieved for the contaminants.

Total suspended solids (TSS): Total suspended solids (TSS) refer to organic and inorganic substances retained by a filter and measured through gravimetric analysis. As a key indicator of water quality, TSS levels are critical for assessing the performance of wastewater treatment processes [35]. Electrocoagulation has demonstrated significant potential for TSS removal; however, its efficiency is highly dependent on the specific industrial application and operational parameters. For instance, in the rubber industry, a system utilizing aluminum and stainless steel electrodes operating at 18V for 150 minutes achieved an 85.39% reduction in TSS [27]. However, the study noted that TSS levels exhibited instability, likely due to electrode decomposition during treatment and differences in voltage measurement that may introduced quantification inaccuracies. In contrast, exceptional results have been achieved in the food industry. A comparative study between electrocoagulation and electro-Fenton processes reported TSS removal efficiencies exceeding 99% for both methods under their respective optimal conditions [36]. This high efficiency is attributed to a greater electrode dissolution rate, which promotes the formation of active coagulants. The authors further clarify that elevated TSS concentrations contribute directly to increased water turbidity, thereby raising the oxygen demand required for organic matter degradation.

In addition, the versatility of the technology is highlighted by its use in the electroplating sector. An electrocoagulation-flotation system employed as a primary treatment for petroleum refinery wastewater achieved a 90% TSS removal efficiency. This performance was measured under optimized conditions, including a current density of 11.3 mA/cm², an initial pH of 6.8, a temperature of 30 °C, a 30-minute treatment time, and a gas flow rate of 0.8 L/min (Table 1) [37].

Further advancements in the textile industry have explored electrocoagulation using pulsed direct current. With stainless steel electrodes, an agitation speed of 200 rpm, a pulse frequency of 1.0 Hz, a 1 mm electrode gap, and a 50-minute treatment time, a 50% TSS removal efficiency was observed [10]. This study underscores that electrode material has a direct impact on pollutant removal rates and recommends further investigation to establish its precise effect on final effluent quality.

Biochemical Oxygen Demand (BOD): The biochemical oxygen demand (BOD) is an analytical parameter that quantifies the amount of oxygen consumed by microorganisms to decompose organic matter in water, serving as a critical indicator of wastewater pollutant load [35]. Electrocoagulation has proven to be an effective technology for reducing BOD across various industries. In the rubber industry, for example, a system employing aluminum and stainless steel electrodes operating at 18 V for 150 minutes achieved a significant BOD reduction of approximately 57%, markedly improving wastewater quality (Table 1) [27]. As the authors explain, a high BOD level signifies a substantial concentration of organic pollutants, which elevates the oxygen demand for microbial decomposition. Even more pronounced results have been demonstrated in the soft drink industry. Using iron and aluminum electrodes with a 2-hour treatment time and the addition of 0.5% bittern a concentrated solution of chlorides, sulfates, and other minerals a remarkable BOD removal of nearly 95% was attained [38]. This high efficiency is likely attributable to the synergistic effect of the sufficient electrocoagulation time and the addition of bittern, which enhances ionic conductivity and promotes coagulation. Similarly, exceptional performance was observed in the fishing industry. The electrocoagulation-flotation process, configured with 8 aluminum electrodes, a 10 mm inter-electrode distance, a 5 A direct current, and a 15 V potential, yielded a 97.5% BOD removal efficiency [39]. The researchers attribute this success to the optimized current density and voltage potential, which intensify the electrochemical reactions necessary for the breakdown of organic pollutants.

Chemical Oxygen Demand (COD): The chemical oxygen demand (COD) is a critical parameter for assessing wastewater pollution, measuring the total quantity of oxygen required to chemically oxidize organic matter in a water sample [35]. The efficacy of electrocoagulation in reducing COD has been demonstrated across diverse industries, though with varying outcomes dependent on specific operational parameters. In the rubber processing industry, a system utilizing aluminum and stainless steel electrodes achieved a moderate COD reduction of 56.14% (Table 1) [27]. In contrast, significantly higher efficiencies have been reported in sectors with high organic loads. For the combined dairy and meat industry, researchers using a 13-electrode iron configuration at 12 V for 60 minutes reported maximum reductions of 96% for total COD and 95% for soluble COD (Table 1) [8]. The authors note that the elevated initial COD values are likely due to the complex matrix of suspended solids, dissolved substances, and significant organic load characteristic of these mixed operations.

Similarly, exceptional performance was observed in the sugar industry. Employing iron, aluminum, and copper electrodes at an optimal pH of 6, a current density of 156 A/m², and a remarkably short treatment time of 15 minutes, a COD reduction efficiency of 97.8% was achieved (Table 3) [40]. This high efficiency is attributed to the increased current density, which accelerates the formation of metal ions that destabilize and remove contaminant particles.

In turn, demonstrated the process's versatility, in the textile industry utilizing pulsed direct current with an agitation speed of 200 rpm, a pulse frequency of 1.0 Hz, and a 1 mm electrode spacing achieved 81.23% COD removal within 50 minutes (Table 1) [10]. This work highlights that electrode material is a critical factor directly influencing removal rates and recommends further study to optimize this variable.

Finally, consistent high performance has been documented in the challenging context of oil refinery wastewater. One study using a cylindrical reactor with aluminum and stainless steel electrodes at pH 6, a current density of 35 mA/cm², and a 120-minute treatment time achieved 90% COD removal [29]. The authors found that neutral pH and increased current density were key to this favorable outcome. Corroborating these findings, another study in the same industry reported a similar 90% COD reduction under conditions of 11.3 mA/cm² current density, pH 6.8, and a 30-minute coagulation time (Table 1) [37]. This research further concluded that the COD removal rate exceeded 90% and that the efficiency of the airlift electrocoagulation reactor is governed by both the applied current density and the fluid flow rate.

Nitrates: Nitrates, characterized by nitrogen in its highest oxidation state, are a naturally occurring ion within the nitrogen cycle. While chemically stable, they can be reduced through microbial denitrification [41]. In water analysis, nitrate concentration is typically quantified via ultraviolet spectrophotometry at 275 nm and serves as a key parameter for monitoring waters with low organic matter content [35]. The efficacy of electrocoagulation (EC) for nitrate removal appears to be industry-specific, with notable success in certain food processing sectors. A study on poultry and dairy slaughterhouse wastewater demonstrated that a sequential treatment combining anodic oxidation (EOR) with electrocoagulation achieved near-total nitrate removal (~99%) (Table 1) [31]. The optimized system, employing stainless steel electrodes across a broad pH range (2-12) and treatment times up to 360 minutes, leveraged the synergistic effect of both processes. This combined approach effectively addressed the complex mixture of pollutants, producing an effluent suitable for discharge or reuse. Beyond industrial wastewater, electrocoagulation has also been applied to remediate nitrate-contaminated groundwater. Research by [42], using aluminum electrodes at 30 V, a 1.8 cm electrode gap, and a 120-minute treatment time, reported consistent nitrate removal efficiencies between 88.48% and 94.1% across various water samples.

Prospective Electrocoagulation Processes in Agro-industries

Electrocoagulation technology has been shown to be a very viable alternative in the removal of organic and inorganic contaminants from various water sources (municipal water, wastewater, lake water, river water and seawater) [26]. Based on the various scientific studies carried out on the subject, a scientific surveillance study was planned, using different search tools such as ScienceDirect, Google Scholar and Scopus to filter documents with necessary and coherent information, with a time range from 2016 to 2022. Likewise, the use of VOSviewer made it possible to purify all the information obtained from Scopus and to establish intercorrelated thematic lines, taking into account a series of keywords and obtaining as a result the thematic map shown in Figure. 4, which consists of five (5) clusters related to the electrocoagulation process. The following is a description of each cluster obtained:

Red cluster: Integrated Wastewater Treatment Strategies

This cluster centers on broader wastewater treatment frameworks, highlighting terms such as electric field, biological treatment, bioremediation, and denitrification [43](Fig. 4). It acknowledges that while many treatment processes exist, they often face limitations in cost, efficiency, time, or the generation of secondary waste [18]. A significant research prospect emerging from this cluster is the development of hybrid systems that combine electrocoagulation with other technologies to enhance removal efficiencies across different effluent types.

Green cluster: Electrocoagulation Performance and Parameters

This group focuses directly on the electrocoagulation process as a versatile technology for wastewater treatment. It shows a strong emphasis on key performance indicators like turbidity, color, and chemical oxygen demand (COD) removal (Fig. 4). Critical operational factors such as the use of aluminum anodes and overall treatment efficiency are also prominent, as these are fundamental to process performance [23]. A notable gap is the relative limited attention given to other crucial parameters like biological oxygen demand (BOD), phosphates, total suspended solids (TSS), and total solids (TS). Future research should aim to include these parameters to provide a more comprehensive evaluation of treatment efficacy for specific agro-industrial effluents.

Purple cluster: Comparison with Chemical Coagulation

The prominent theme here is chemical coagulation, a conventional process where chemicals are added to remove impurities via agglomeration and precipitation [18]. A study in the pharmaceutical industry [44] compared this method with electrocoagulation, finding chemical coagulation with alum and FeCl3 removed only 14.05% and 26.3% of total dissolved solids (TDS), respectively. In contrast, electrocoagulation achieved superior removal of both COD (92.3%) and TDS (91.5%). This comparison highlights a significant research opportunity: the systematic evaluation of combined coagulation-flocculation and electrocoagulation processes for agro-industrial wastewater, where such hybrid approaches are still underexplored.

Yellow cluster: The Role of Natural Coagulants

This research line connects electrocoagulation with natural coagulants. Key terms include biochemical oxygen demand and water purification. For instance, *Tamarindus indica* seeds were used as a natural coagulant in the dairy industry, achieving 71% TDS and 75% COD removal [45]. Another study on pharmaceutical wastewater achieved a 78.23% COD reduction using a combination of natural and chemical coagulants with electrocoagulation [44]. A study compared combined treatment processes using coagulation-flocculation (CF) and electrocoagulation techniques in wastewater from the pharmaceutical industry (PIWW), using natural coagulants and chemical coagulants, achieving a COD reduction percentage of 78.23 %. The terms coagulation-flocculation refer to physicochemical processes that have the potential to reduce pollution and provide clean water for reuse in water and wastewater treatment (Fig. 4). Although this term is related to the electrocoagulation process, there are few studies in which these combined systems have been used, however, in agro-industrial processes there are scientific gaps in terms of wastewater treatment, which would be a good prospect for future research.

Blue cluster: Process Mechanisms and Hybrid Technologies

This cluster describes the fundamental phenomena of the electrocoagulation process, highlighting concepts such as electrode degradation, presence of anodes, cathodes, and electro-oxidation processes (Fig. 4). It is also related to alternative technologies such as activated carbon treatments, which is used as an absorbent due to its large surface area and high absorption rate of organic and inorganic contaminants [43]. In addition, advanced ultrasound-assisted oxidation processes for complex effluent treatment, as it has a remarkable impact on the efficiency and removal of pollutants. According to [46] showed in their research an average pollutant removal efficiency of more than 90 % for color, turbidity, BOD, oil and grease, using electrocoagulation-ultrasound-assisted flotation (ECF/US) processes and Al/Fe electrodes with a treatment time of 25 min.

It is important to highlight the need for future research studies to quantify reductions in electrode material consumption, sludge production, and energy use during the electrocoagulation process.

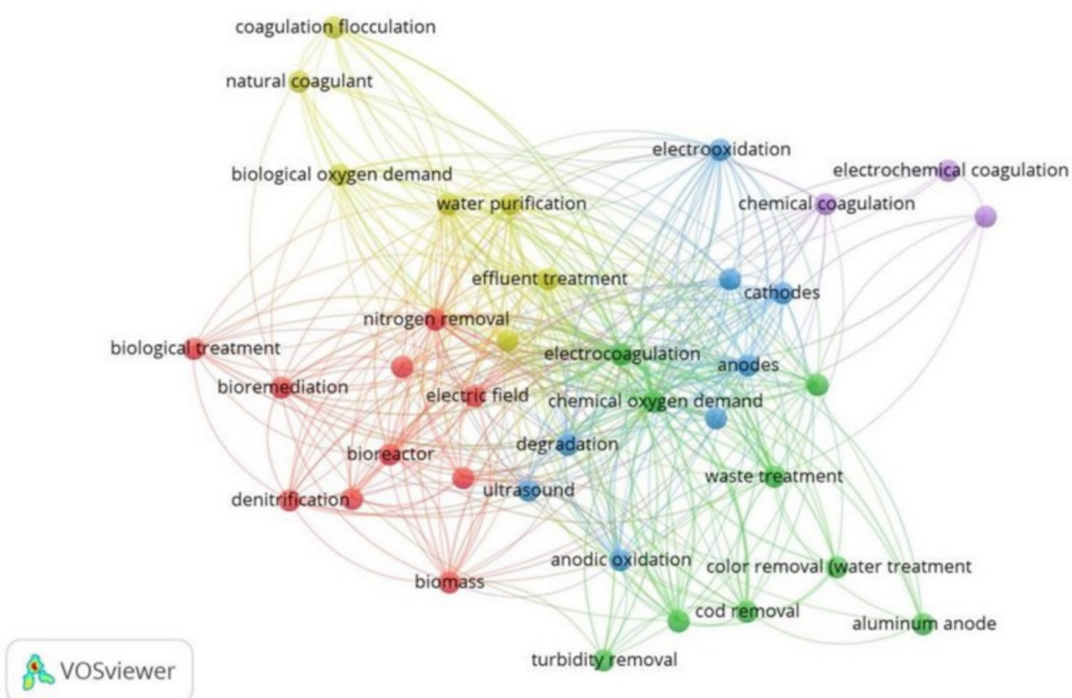

Figure 4. Cluster of scientific surveillance related to the electrocoagulation process.

Note. **Source:** Own elaboration

Although the electrocoagulation technique shows high potential for removing contaminants from various water sources, it still lacks large-scale implementation, as most of the published studies have been conducted on a laboratory scale, providing only a small amount of information. Therefore, further research is needed to study the impact of new reactor designs, electrode configuration, electrocoagulation mechanisms, processing conditions, and electrode dissolution phenomena. Additional analysis is also required to determine the operating conditions of the process at the agro-industrial level. Also, future studies should be conducted on the reduction of electrode consumption and process efficiency on water quality properties.

Table 1. *Application of the electrocoagulation process for the treatment of various industrial effluents.*

Industry	Electrodes	Optimal conditions	Removal efficiency (%)	Water quality properties	Reference
Rubber industry	Aluminum and stainless steel	Voltage of 18V and processing time of 150 min.	56.14	An effective reduction of TSS of 85.39 %; COD 56.14 %; BOD 57.18 % and NH3 73.5 % was achieved.	[27]
Cardboard industry.	Aluminum	pH of 6.62, electric current of 10A, electrode spacing of 3 mm, KCl at 0.5 mg/L.	54	The EC technique obtained a COD efficiency of 54 %, color and turbidity greater than 95 %.	[34]
Soft drink industry	Iron and Aluminum	The operating time at the levels was 2, 4 and 6 min.	98.31	A COD removal rate of 98.31 % and BOD removal rate of 95.00 % was achieved.	[38]
Sugar Industry	Mild steel	Treatment time was 100 min, pH 6.66 and DC of 104 A/m^2.	75.98	The EC had a COD removal rate of 75.98 %.	[47]
Potato processing industry	Aluminum	pH between 6 and 7.5, time of 20 min, DC greater than 1.6 and conductivity above 4.	70	The EC process achieved a COD removal of more than 70 %.	[48]
Domestic wastewater	Iron and Aluminum	pH between 7 and 8.2, current intensity of 7 A and time of 15 min.	80	Electrocoagulation achieved a COD removal greater than 80 %.	[49]
Food industry	Iron	Time 21 and 36 min, pH 10 and current density 86 mA/cm^2	59.1	The EC obtained a high COD removal of 59.1 % and TSS removal of more than 99 %.	[36]
Textile Industry	Stainless steel	stirring speed of 200 rpm, pulse frequency of 1.0 Hz, electrode distance of 1 mm and time of 50 min.	81.23	The EC process obtained a COD reduction of 81.23 %; color 98.94 %; turbidity 85.87 %; TSS 45.98 %; sulfate 98.75 % and sulfide 55.2 %.	[10]
Swine industry	Iron and Aluminum	DC of 2.94 mA/cm^2 and a reaction time of 60 min.	81	The EC allowed a reduction of COD up to 81 %; color of 82 % and ST of 91 %.	[50]
Sugar Industry	Iron, aluminum and copper.	pH 6, DC 156 A/m2, electrode distance 20 mm, treatment time 15 min.	97.8	The EC showed a COD reduction of 97.8% and a color removal of 99.7%.	[40]
Dairy and meat industry	Iron	13 electrodes, DC at 12 V, electrode spacing of 20 mm and a reactor operating time of 60 min.	96 & 95	The process achieved a total COD removal of 96 %, soluble COD of 95 % and turbidity of 94 %.	[8]
slaughterhouse industry	Aluminum and Iron	10 electrodes, electrode spacing of 1 cm, DC in the range of 4.54 to 18.18A/cm^2 and treatment time 60 min.	79	The EC assisted with anaerobic digestion obtained a removal of more than 79% of COD, 95% of nitrate and 90% of turbidity.	[24]
Lacto Whey Industry	Iron, Aluminum and Stainless Stee	Fe / AISI 304	* (COT) 49.1	The EC process produced a higher removal (TOC) of 49.1 %.	[51]

Continued Table 1.

Industry	Electrodes	Optimal conditions	Removal efficiency (%)	Water quality properties	Reference
Pig Slaughterhouse	Aluminum and Aluminum/ Iron	5 A DC, 6 V potential, 10 mm electrode spacing and 60 min time, with Al electrodes.	*Color 97; turbidity 97.4; BOD 93 & oil and grease 90.	The EC with Al electrodes, obtained removal of color 97 %; turbidity 97.4 %; BOD 93 %, oil and grease 90 %; Al/ Fe removal of color 95.5 %; turbidity 96.2 %; nitrogen 93.4 %; and BOD 90.7 %; oil and grease, was < 90 %.	[52]
Electroplating	Iron and Aluminum	pH 9, DC of 2 mA/cm^2	*Removal of heavy metals (Cu, Zn, Ni and Cr).	The EC process showed higher removal efficiency of heavy metals about 90 % (Cu, Zn, Ni and Cr).	[33]
Paper industry	Aluminum	pH 7.0, current density 24.80, treatment time 50 min, with 100 rpm and an electrolyte dose of 1 g/L.	68	The EC process had COD, Color, TOC and TDS removal efficiencies of 68 %, 94 %, 67 % and 37 %.	[53]
printing ink industry	Aluminum	DC of 21 mA/cm^2, electrode spacing of 3mm and, treatment time 120 min	88	The EC process obtained a COD removal rate of 88 %, color 99 %, and TSS reduction of 98 %.	[54]
Sugar industry	Aluminum	pH 7, reaction time of 60 min and electrical power of 10 and 30 V.	*Phosphate 99.38	The EC technique obtained a phosphate removal of 99.38 %.	[55]
Textile industry	Iron	10 electrodes, pH 8.24, electrode spacing 4 mm, voltage 70 V.	90.16	The continuous electrocoagulation-adsorption processes showed a removal of color, COD and TSS of 96.87 %, 89.77 % and 84.46 %.	[56]
Licorice extract powder production industry.	Iron	Electrolysis time of 70 to 90 min and an average DC of 250 to 450 A/m^2.	89.4	The EC technique achieved 90.1 % color removal; COD 89.4 %; turbidity 82 % and alkalinity 73.3 %.	[57]
Industrial Tanneries.	Aluminum	Treatment time 40 minutes and a DC of 6 mA/ cm^2	70	The technique showed a COD reduction of 70%; TSS, chromium (III) and turbidity had a removal greater than 90 %.	[58]
Textile dyeing factory.	Aluminum	Initial pH of 5.5, DC current of 15 mA / cm^2 and an EC time of 23 min	*Color 98	The percentage of decolorization in the wastewater was 98%.	[59]
Oil refinery	Aluminum and stainless steel.	pH 6, current density of 35 mA/ cm^2 and treatment time of 120 min. 90	90	Through the EC process a COD removal of 90 % and a turbidity reduction of 75 % was obtained.	[11]

Note. **Removal** efficiency measured through COD. CD, current density; EC, electrocoagulation; TSS, total suspended solids; TP, total phosphorus; TOC, total organic carbon; BOD, biochemical oxygen dem and *Removal measured through other parameters.

Source: own elaboration

CONCLUSIONS

The electrocoagulation (EC) process has demonstrated remarkable versatility and effectiveness across a wide range of industrial wastewater sources, including the food, dairy, meat, textile, electroplating, rubber, sugar, oil refinery, and paper industries, among others. This adaptability arises from EC's ability to remove various contaminants organic matter, nutrients, heavy metals, dyes, and suspended solids through electrochemical oxidation, coagulation–flocculation, and adsorption mechanisms.

In the food and dairy sector, EC systems using iron electrodes have achieved removal efficiencies of up to 96% for total COD, 95% for soluble COD, and 94% for turbidity, thus demonstrating their strong capacity to remove both particulate and dissolved organic fractions. Likewise, the meat and slaughterhouse industries have benefited from EC combined with anaerobic digestion, achieving reductions above 79% for COD, 95% for nitrates, and 90% for turbidity, confirming its potential as a pre- or post-treatment step to enhance biodegradability and improve effluent quality.

For the textile and dyeing industries, characterized by high loads of persistent dyes and surfactants, EC using stainless steel or aluminum electrodes has achieved COD removal rates between 81% and 90%, and color removal above 98%. These findings indicate that EC efficiently degrades chromophoric groups and complex organic compounds, which are often responsible for the high toxicity and low biodegradability of textile effluents. Similarly, in the printing ink industry, EC achieved 88% COD, 99% color, and 98% TSS removal, which highlights its suitability for treating highly pigmented effluents. The sugar industry has also shown excellent results with EC, achieving up to 97.8% COD and 99.7% color removal when using mixed electrodes (Fe, Al, and Cu) under optimal pH and current density conditions. Additionally, EC has proven effective in removing specific pollutants such as phosphate ions, with efficiencies as high as 99.38%, contributing to the mitigation of eutrophication in receiving water bodies.

In oil refinery wastewater, where high concentrations of hydrocarbons and emulsified oils are common, EC with aluminum and stainless steel electrodes has achieved 90% COD and TSS reduction, even under neutral pH conditions. These results demonstrate that EC effectively destabilizes oil–water emulsions and significantly decreases the organic load, improving the potential for effluent reuse. Other industrial sectors, such as electroplating, have benefited from EC's ability to remove heavy metals (Cu, Zn, Ni, Cr) with efficiencies above 90%, highlighting its role as an eco-friendly alternative to chemical precipitation. Likewise, in the fishing and poultry processing industries, EC achieved simultaneous removals of COD (93%), BOD (97%), turbidity (97%), and oils and fats (94%), considerably improving overall water quality.

From an environmental perspective, electrocoagulation is emerging as a sustainable alternative for industrial wastewater treatment. Unlike conventional chemical coagulation, this process generates smaller volumes of less toxic sludge, facilitating final disposal and even enabling its potential valorization. Additionally, the treated effluent achieves sufficient quality for reuse in irrigation or industrial cleaning, promoting water circularity particularly in regions facing water stress. However, large-scale implementation still presents technological and economic challenges. Electrode passivation, energy consumption, and the lack of standardization in reactor designs are barriers that require attention. To overcome them, it is strategic to integrate electrocoagulation with complementary technologies such as advanced oxidation processes, bioelectrochemical systems, or renewable energy sources along with developing predictive models and life cycle assessments that quantify its environmental benefits. In this way, electrocoagulation can definitively position itself as a clean, efficient, and sustainable technology for the comprehensive management of industrial wastewater.

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