Progress in Energy and Environment

Journal homepage: https://progeenv.com/index.php/journal/index

Link to this article: https://doi.org/10.37934/progee.32.2.122

Vol. 32 Issue 02 (2026) 1-22

Review Article

Electrocoagulation Technology for Oil Removal in Food Wastewater: Research Trends and Patent Landscape Analysis

OPEN ACCESS

Jillin Ai Lam Soo[1], Tzen Tshen Heng[1], Lian See Tan*[,1], Khalid Shihada Amir Ahmad[1], Noor Fazliani Shoparwe[2], Mohamed Mahmoud El-Sayed Nasef[1], Sinung Suakanto[3]

[1] Department of Chemical and Environmental Engineering, Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia, 54100 Kuala Lumpur, Malaysia

[2] Faculty of Bioengineering and Technology, Jeli Campus, Universiti Malaysia Kelantan, 17600 Jeli Kelantan, Malaysia

[3] Department of Information System, Telkom University, Bandung 40257, Indonesia

* **Correspondence email:** tan.liansee@utm.my

Abstract

The increasing demand for edible oils in food processing has resulted in substantial oily wastewater generation, posing challenges to global water security. This review examines electrocoagulation technology for treating oil pollutants in food industry wastewater through analysis of peer-reviewed journal articles and a broader patent landscape analysis across all industrial sectors. Electrocoagulation generally achieved high oil removal efficiency across the reviewed studies, though COD removal performance was more variable, indicating strong effectiveness for oil separation but inconsistent overall organic load reduction. Literature analysis revealed that key operational parameters include electrode material, electrolysis time, pH, supporting electrolyte concentration, applied voltage, and initial oil concentration. Patent analysis revealed a growing commercial interest, with the United States leading, followed by international patent applications (via the World Intellectual Property Organisation, WIPO) and China. Patent trends show a steady growth from 2017 onwards. Several challenges including electrode passivation, energy consumption, and by-product/sludge management, which limit widespread applications need to be addressed. Recommendations to enhance commercial viability include integration of not only renewable energy and Artificial Intelligence (AI) for energy optimisation but also life cycle assessments/life cycle cost analysis to objectively evaluate environmental and economic impacts and sludge valorisation for circular economy applications. This is to bridge laboratory research and commercial implementation for sustainable food wastewater treatment.

Article Info

Received: 3 October 2025

Received in revised form: 30 April 2026

Accepted: 4 May 2026

Available online: 12 July 2026

Keywords

Electrocoagulation

Oil-water Separation

Food Industry

Wastewater Treatment

Pollutant Removal

1. Introduction

Wastewater generated from the food industry poses a significant environmental hazard that demands urgent attention. Food industry effluents are typically rich in organic matter, nutrients, fats, oils, and greases, and may also contain pathogenic microorganisms and trace amounts of heavy metals. Among these contaminants, oil-based pollutants represent one of the most critical challenges, as they not only impair water quality but also hinder natural biodegradation processes, reduce dissolved oxygen levels, and exert toxic effects on aquatic ecosystems. If left untreated, oily wastewater can cause long-term environmental damage and pose serious risks to public health, underscoring the need for effective and sustainable remediation strategies. A major source of oily wastewater is the widespread use of edible oils in food processing industry. Global demand for edible oils is projected to grow at a compound annual growth rate (CAGR) of 4.8% between 2022 and 2027 [1], implying a parallel increase in oily effluent generation. On a broader scale, it is estimated that approximately half a million tons of such oils are discharged annually into marine environments from land-based sources including food-processing facilities, agriculture, and urban runoff [2], highlighting their contribution to global waste and water pollution burdens.

Grease traps are commonly used to remove free-floating oil by gravity separation. Any oil residue that remains in the wastewater, including dispersed, emulsified and dissolved oil, must be removed in further treatment stages. The removal of such oil residue from wastewater is a complex process, particularly when dealing with emulsified oil [3]. Emulsified oil is a persistent form of oil particle found in wastewater. It is formed when oil and water mixture is subjected to high-speed mixing or turbulence which results in high shear force that weaken the interfacial tension between the oil and water molecules [4]. As a result, oil breaks into smaller droplets and disperses throughout the mixture. Oil droplets can also be stabilised with the addition of emulsifying agent by changing charge density of the oil molecules and enhancing electrostatic repulsion between emulsified oil droplets [5].

There are various methods that have been developed for the removal of oil from oily wastewater. Chemical coagulation/floatation treatment involves addition of chemicals to destabilise emulsified oil droplets, which subsequently aggregate into larger flocs that can be separated more easily. Although effective, this method is often considered environmentally unsustainable due to its high chemical demand, the generation of large volumes of chemical sludge, and associated disposal challenges. Membrane filtration, in contrast, separates oil droplets primarily through size exclusion. This process offers high treatment efficiency and reduces the need for chemical additives, making it comparatively more environmentally benign. However, it faces challenges due to issues such as membrane fouling, sensitivity to feedwater characteristics, and susceptibility to thermal degradation. Electrocoagulation, on the other hand, employs sacrificial metal electrodes to release coagulant species in situ, which hydrolyse and destabilise oil droplets, forming flocs that can be readily separated. This technique requires minimal or no external chemical addition, generates lower sludge volumes, and can be more cost-efficient than conventional approach [6].

In recent years, electrocoagulation is explored as a promising alternative for treating emulsified oil-containing wastewater from the food processing industry. Electrocoagulation technology has gained the attention of researchers due to its flexibility and low footprint [6]. Furthermore, electrocoagulation treatment produces at least 60% less volume of sludge compared to chemical coagulation, hence reducing the amount of solid waste generated that requires further handling [7, 8]

Several reviews on the application of electrocoagulation for oily wastewater have been published in recent years. For example, Kadier et al. [6], Shokri and Fard [9], Jasim and Aljaberi [10], and Muvel et al. [11] reviewed the advances in electrocoagulation for oily wastewater treatment across a range of industrial applications including oilfields, petroleum processing plants, metal processing & finishing, food processing, tannery, and restaurants. However, these reviews either provide a broad overview of electrocoagulation for oily wastewater across multiple industries [6,9] or focused on the mechanism and optimisation of the electrocoagulation process for oily wastewater [6,9,10,11]. For the aforementioned reviews, the oily wastewater treatment from the food processing industry is only briefly mentioned. Shokri and Fard [9] very briefly described only one application of electrocoagulation in food processing wastewater treatment. A deeper review was undertaken by Kadier et al. [6] that by describing the treatment of oily wastewaters from food processing industries, slaughterhouses and restaurants. Yet, their coverage relied predominantly on studies published before 2020. As will be discussed later (Section 2.0), research on electrocoagulation in food processing wastewater has increased substantially since 2020. Thus, valuable recent development and optimisation strategies have not been captured in earlier reviews. This highlights the need for an up-to-date analysis of electrocoagulation technologies for oily wastewater treatment in the food processing sector.

Hence, the objectives of this review are to provide a structured overview of electrocoagulation technologies specifically applied to the treatment of oily wastewater from various food industries, to evaluate the operational parameters that influence electrocoagulation efficiency within the context of food-industry effluents, and to analyse patent trends across multiple industrial sectors to assess commercial interest in electrocoagulation for wastewater treatment and its potential relevance to food wastewater applications. By integrating insight from both literature and patent landscape, this work highlights current advancements, emerging trends, and challenges to scale up this technology for industry adoption. This approach allows recommendations be guided by both the food-focused literature and the wider technological developments evident in patent trends.

The scope of this article includes a bibliographic review covering the period from 2000 to 2024 to analyse the research interest in the application of electrocoagulation for treatment of oily wastewater from various food industries, and the insights gained from those previous research. This was coupled with patent analysis conducted from 2014 to 2024 across all industrial sectors. The patent analysis was intentionally broadened to identify potential technology adaptation opportunities. Furthermore, the increasing patent volume across multiple sectors reflects substantial technological activity in electrocoagulation beyond academic research, which is relevant when evaluating its potential applicability in the food industry. Thus, the cross-sector patent landscape offers insights into technological options that could be adapted for this sector. This analysis also examined patent trends, identified key industrial players and jurisdictions, providing insight into the practical implementation potential and commercial interest in electrocoagulation for wastewater treatment applications. This approach could better illustrate the technological progress, remaining challenges, and prospects of electrocoagulation in wastewater treatment worldwide.

2. Methodology

A scoping review of the literature was conducted using the Scopus database to identify relevant journal articles on the application of electrocoagulation for oily wastewater treatment in food industries. The combined keyword search of “electrocoagulation” and “food wastewater” was applied, covering publications from 2000 to 2024. The search was limited to research articles published in English. A total of 41 relevant publications were identified after screening based on title and abstract reading to confirm relevance to electrocoagulation treatment of oily wastewater from food industry sources. Articles that did not relate to food industry wastewater or oil-based pollutant removal were excluded from the analysis.

Thereafter, to evaluate the commercial interest and technological development of electrocoagulation in wastewater treatment, a patent landscape analysis was conducted for the period

2014–2024 using the Lens.org database that encompasses worldwide patent filings. The search was performed with the Boolean search string keywords “electrocoagulation” and “wastewater treatment”. The term “food” was intentionally excluded to capture a broader landscape that includes technology adaptation opportunities and cross-sector technological activity, as justified in the Section 1.0.

The search was conducted in May 2025, only patents filed and granted within 1st January 2014 to 31st December 2024 were considered for analysis. The analysis includes both patent applications and granted patents to identify emerging trends as well as established intellectual property. The analysis excludes patents that do not relate to wastewater treatment for the purpose of producing drinking water. Duplicated patents across multiple jurisdictions are also excluded and consolidated into a single patent filing with respect to the earliest application granted. Patent screening was done through title and abstract reading to determine relevance. Further patent reading was undertaken for patents of uncertain information. Extracted patent information was then divided into patent year, number of patents, patent applicants, and jurisdiction for easier trend analysis. The patent analysis was conducted as a landscape analysis, with emphasis on identifying general trends in patent activity, key applicants, and jurisdictions, rather than providing a detailed technical breakdown of individual electrocoagulation patents.

3. An Overview of Electrocoagulation Process in Food Wastewater Treatment

Since the early 2000s, scholarly interest in the application of electrocoagulation for food wastewater treatment has shown a steady increase, with 41 relevant publications identified over the 24-year period from 2000 to 2024. This reflects the growing recognition of electrocoagulation as a viable treatment strategy for oily effluents generated by the food industry. Figure 1 illustrates the number of journal articles published on electrocoagulation for food wastewater (real and simulated) from 2000 to 2024. It can be observed that over the past 10 years, the number of publications on food electrocoagulation studies has been steadily increasing. The types of food wastewater considered in previous studies are also analysed and the breakdown with respect to industrial sources is illustrated in Figure 2. Detailed information on oil removal percentages, experimental parameters, and the specific food industry applications, including synthetic oil emulsion studies, is provided in Supplementary File as Table S1.

Based on the reviewed journal articles, the effectiveness of the electrocoagulation treatment can be determined by the measuring chemical oxygen demand (COD), as 73% of the studies reported on COD removal [28,29,31] while the remaining 27% reported on oil content removal [9,16,25]. Figure 3 illustrates the COD removal percentage of electrocoagulation technology in treating different sources of food wastewater reported in investigated journal articles. Among the articles reporting COD removal, 37% reported ≥80% COD removal [22,26], 15% reported ≥60% COD removal [21,23], 12% reported ≥40% COD removal [19,24], 8% reported ≥20% COD removal [14,20] and 1% reported <20% COD removal [12]. Regarding oil removal performance, all reported results were ≥80% [9,18].

Furthermore, electrocoagulation studies were usually conducted with real food wastewater to determine the feasibility of the treatment system for food industry applications. Based on the reviewed articles, 39 out of the 41 articles were conducted with real food wastewater while the remaining 2 articles were conducted with simulated samples. However, the efficiency of the electrocoagulation treatment in removing oil pollutant is difficult to be assessed with real wastewater due to the complex composition of real wastewater.

Real wastewater is rich in organic contaminants, which are high in chemical oxygen demand, biological oxygen demand, and nutrients (nitrogen and phosphorus) [34]. The characteristics of each contaminant differ from one another, causing differences in reaction and treatment process outcomes. Therefore, it is necessary to consider the effects of other contaminants present on the efficiency of electrocoagulation. To provide conclusive results, synthetic oil emulsion was used in some studies.

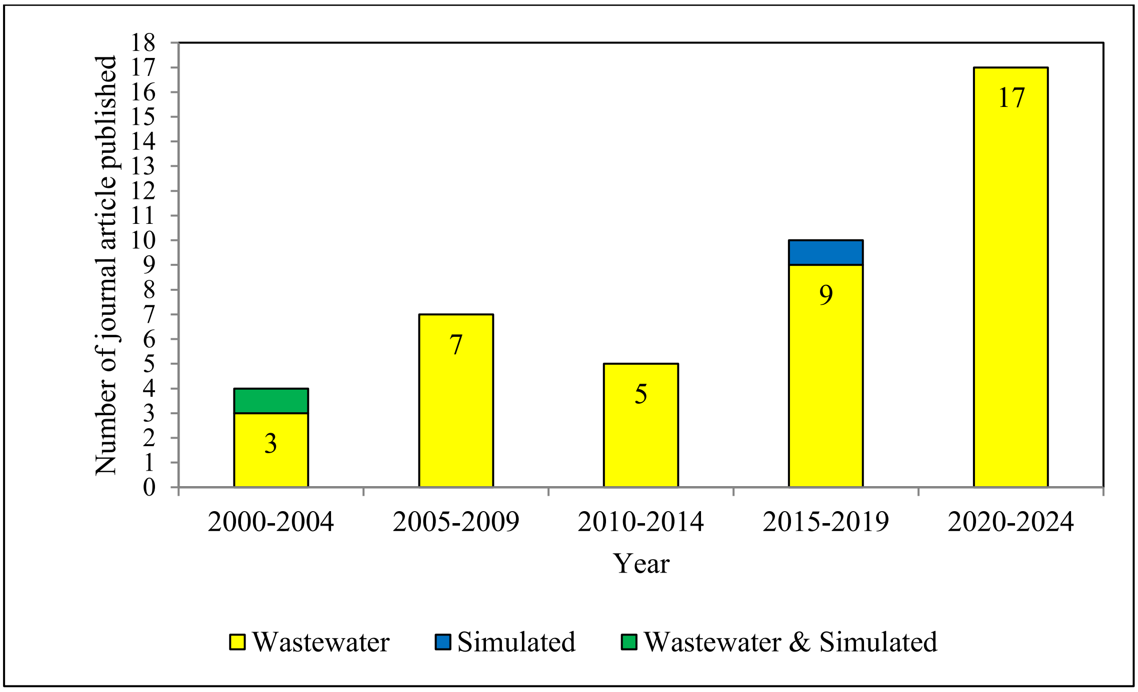

Figure 1. Number of journal articles published on the study of electrocoagulation for real and simulated food wastewater in period from 2000 to 2024.

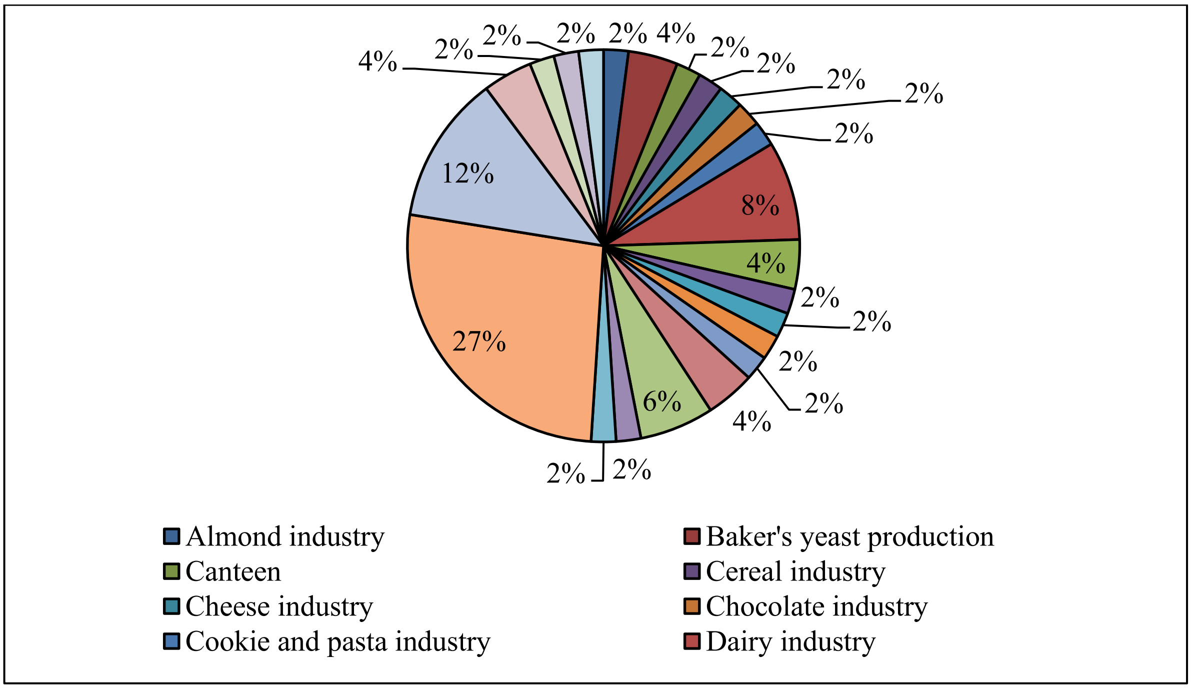

Figure 2. Type and percentage of food industry studied in electrocoagulation treatment from 2000 to 2024.

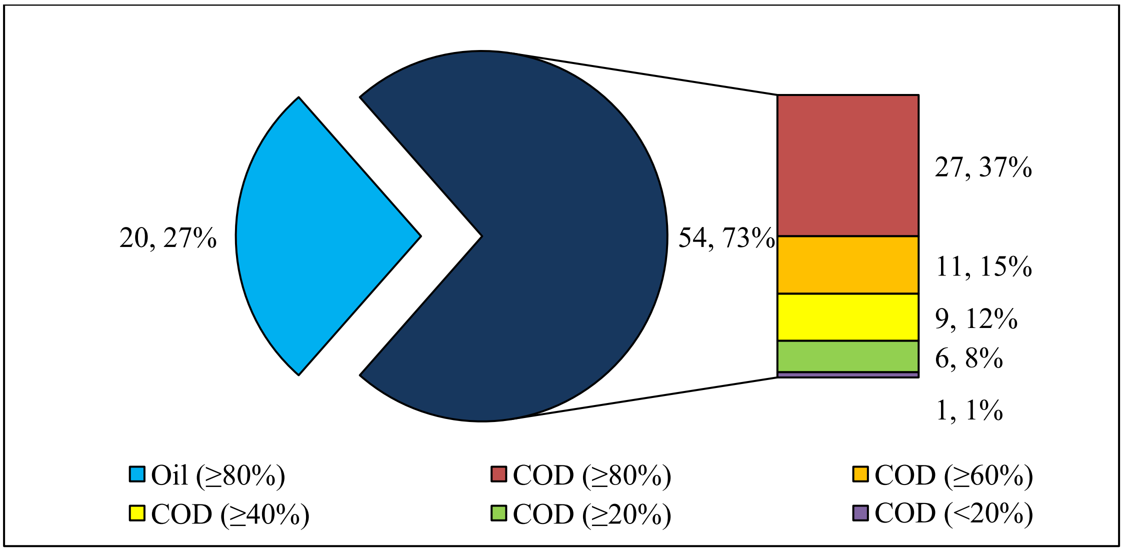

Figure 3. COD removal percentage of electrocoagulation technology in treating different sources of food wastewater reported in investigated journal articles.

Mirshafiee et al. [18] examined the efficacy of electrocoagulation treatment for synthetic oil emulsion prepared with fresh edible oil. They obtained high oil and COD removal at 97.71% and 94.6 ± 0.2% respectively. However, the properties of waste oil differ from fresh oil and may lead to different treatment outcomes. Soo et al. [32] found that under optimised conditions of pH 6.4, supporting electrolyte of 1.228 g/L, applied voltage of 3.251 V and an initial concentration of oil at 1.259 g/L, 98.11% of emulsified waste cooking oil removal efficiency could be achieved.

While the previous studies demonstrated varying removal efficiencies across different food industry applications, the performance of electrocoagulation was also observed to be heavily dependent on several key operating parameters. Understanding and optimising these parameters is crucial for achieving the desired treatment outcomes. The next section examines the key factors that influence electrocoagulation efficiency in food wastewater treatment.

4. Parameters affecting Electrocoagulation Efficiency in Oily Wastewater from Food Industries

4.1. Electrode Material

Electrodes are the main medium used to conduct electrical current throughout the electrolyte in the electrocoagulation process. Hence, the selection of suitable electrodes is imperative to achieving high performance in the electrocoagulation treatment.

Figure 4 presents the types of electrode materials that have been used in electrocoagulation studies for oil removal. The main electrode materials used to study oil removal efficiency via electrocoagulation were aluminium, iron and stainless steel. It can be observed that aluminium and iron electrodes are more commonly used in electrocoagulation studies, accounting for 65% [9,25] and 30% [27,28] respectively. This is due to their ready availability, economical pricing, and proven efficiency.

Based on the analysis shown in Figure 4, aluminium electrode is preferred compared to iron electrode. When a complete circuit is established, the aluminium electrode is readily oxidised into trivalent ion, Al3+ that is used for the formation of in-situ metal coagulant, aluminium hydroxide, Al(OH)3. The Al(OH)3 molecules are responsible for adsorbing and removing the oil molecules. Compared to aluminium electrode, iron electrode would be initially oxidised into divalent ion, Fe^{2+}

prior to trivalent ions, Fe3+ used for the formation of the desired metal coagulant, $Fe(OH)^3$. This means that iron has a slower rate of dissolution and formation of coagulant compared to aluminium, which could result in longer treatment time and higher electrical energy consumption [35].

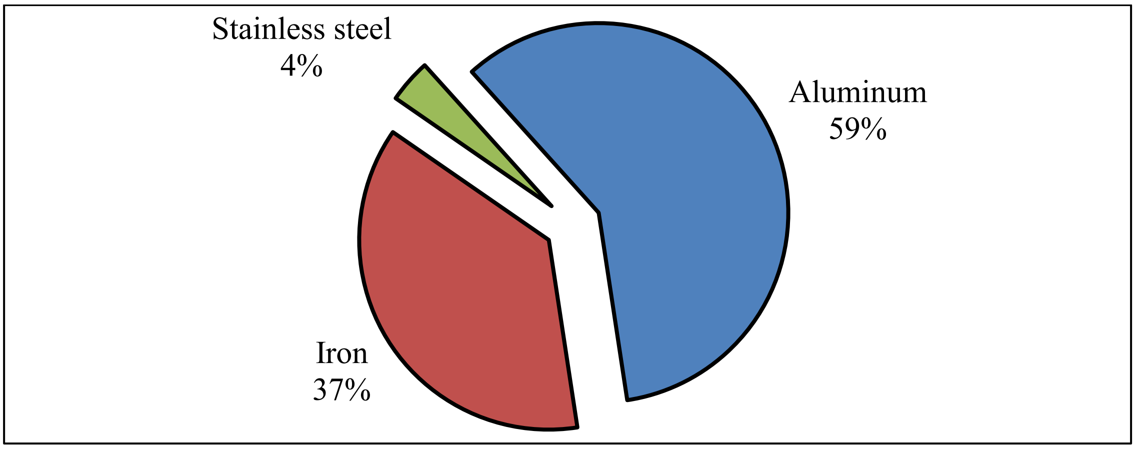

Figure 4. Types of electrode materials for electrocoagulation studies from 2000 to 2024.

4.2. Electrolysis Time

Besides electrode material selection, the duration of treatment plays a critical role in electrocoagulation efficiency. The treated water quality is significantly dependent on the duration of the electrocoagulation treatment. During the treatment, pollutants would undergo several stages of reaction including destabilisation, coagulation and adsorption. It is necessary to allocate sufficient amount of time for each treatment process so that the treatment cycle is complete and efficient. This enhances the reactions occurring at the electrode surface and improves the efficiency of the electrocoagulation process. In accordance with Faraday's law in Equation (1), the amount of metal ions produced in the electrocoagulation system is directly proportional to the electrolysis time.

$$w = \frac{Itm}{zF} \tag{1}$$

where, w is the amount of dissolved metal produced from the anode electrode (g), I is the current (A), t is the electrolysis duration (s), m is the molecular mass of the anode metal (Al = 26.982 g/mol), z is the number of electrons involved in the redox reaction ($z_{Al} = 3$), and F is Faraday's constant (96500 C/mol).

At fixed current density, the dissolution rate of the anodic metal and the cathodic hydrolysis process for producing hydroxide ions is limited. Thus, the electrocoagulation duration dominates the reaction process. Allocating additional time for treatment would generate more metal and hydroxide ions from the electrodes for the formation of metal coagulant that removes the pollutants. However, once the treatment reaches its maximum capability, additional treatment time would provide insignificant increase in the efficiency of electrocoagulation treatment.

Figure 5 shows the various durations allocated for pollutant removal by electrocoagulation treatment based on the reviewed papers. It can be observed that most researchers carried out electrocoagulation treatment for 0 – 30 min [19,28], followed by 31 – 60 min [20, 25], 91 – 120 min [18,30] and a few for 61 – 90 min [18,22]. This is in agreement with An et al. [33], who concluded that the optimal reaction time was 20 – 30 min.

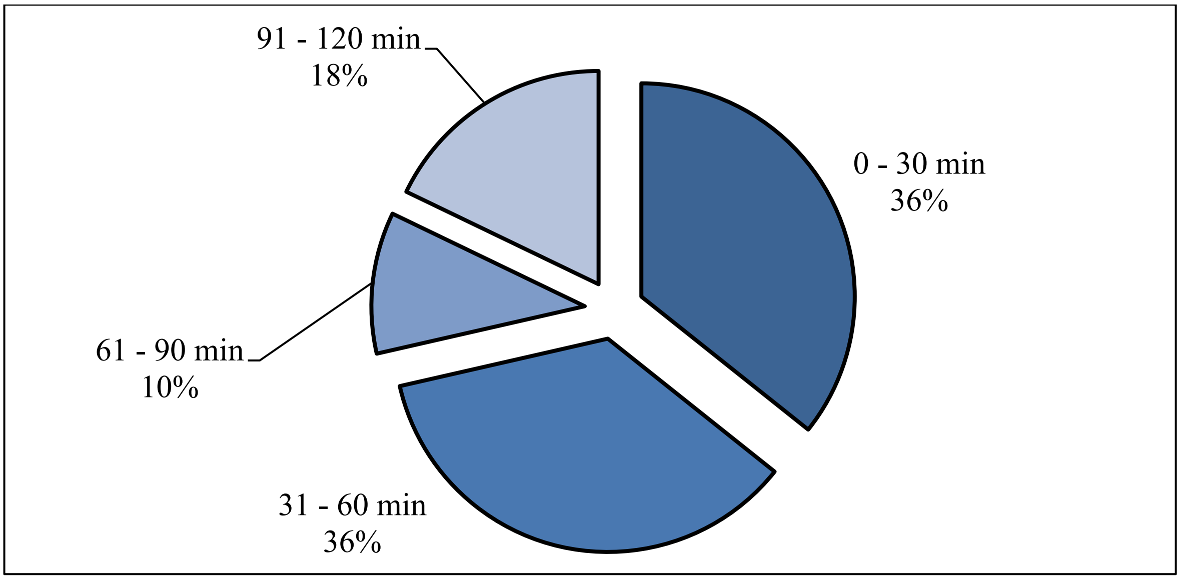

Figure 5. Various durations applied in electrocoagulation treatment studies for food-based wastewater from 2000 to 2024.

4.3. Impact of pH

The pH of the pre-treated wastewater sample also plays an important role. This is because the initial pH would affect the stability of the metal hydroxides produced and alter the electrical characteristics of the molecules, which could impact the efficiency of the electrocoagulation treatment process [36]. In addition, the metal hydroxide formed varies under different electrolyte pH where the range of initial pH studied was between 3 to 8.71 for real food wastewater and synthetic samples.

Figure 6 shows the percentage of oil and COD removal by electrocoagulation treatment for food wastewater under different initial pH values. It can be observed that samples with high removal percentage clustered was around neutral pH (6.5 – 7). This is because the production of metal coagulant, e.g. $Al(OH)_3$, dominates the reactions at neutral pH [37]. Hence, the rate of oil removal is more efficient at neutral pH. When the pH is more acidic, the Al species formed are more positively charged, such as Al^{3+}, $Al(OH)^{2+}$ and $Al(OH)^{2+}$ [37]. These species are suitable for destabilising oil pollutants via charge neutralisation process or electric double-layer compression. However, as the electrocoagulation treatment takes place, the OH^- ions and H_2 gas generated at the cathode would neutralise the acidic electrolyte and increase the pH. This occurs until equilibrium is achieved due to the buffer capability of $Al(OH)_3/Al(OH)_4^-$ generated in the electrolyte [38].

At neutral pH, the adsorption process dominates the treatment and removes oil pollutants. Nevertheless, acidic electrolytes are less efficient because they need to neutralise the electrolyte solution prior to producing $Al(OH)_3$. Similarly, basic electrolytes would induce the production of negatively charged species including $Al(OH)_4^-$, $Al(OH)_6^{3-}$, $Al(OH)_5^{2-}$, and AlO_2^- , which causes less effective flocculation and a downturn of the performance of the electrocoagulation treatment [39]. This occurs because of the repulsion effect between both of the negatively charged species and oil pollutants that jeopardises the destabilisation and adsorption process of the electrocoagulation treatment [12]. Hence, lower removal percentage in electrocoagulation treatment is obtained in basic electrolytes.

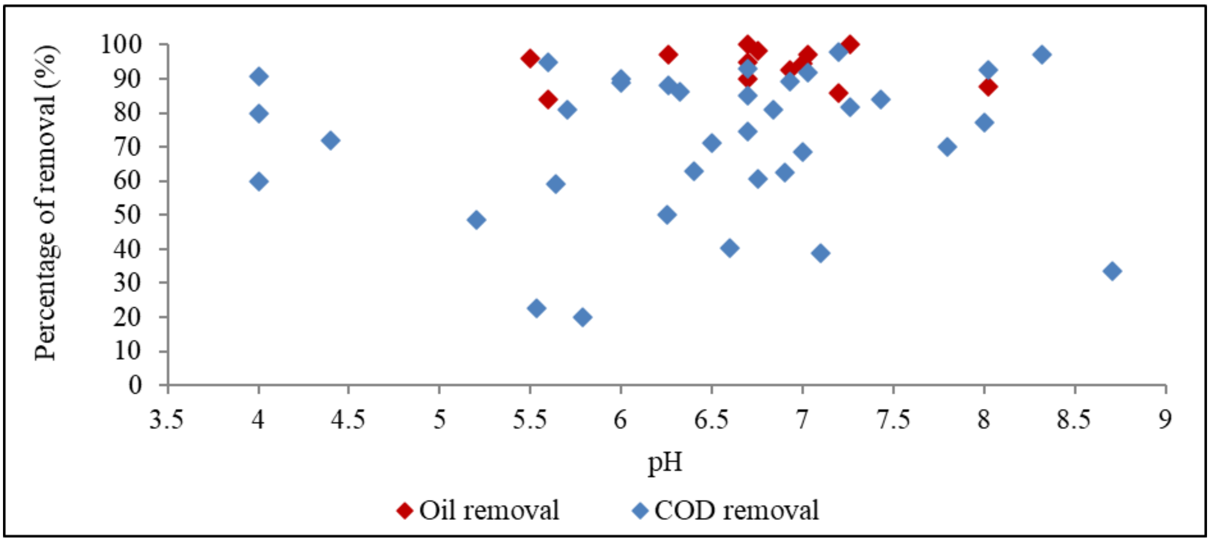

Figure 6. Percentage of oil and COD removal by electrocoagulation treatment for food wastewater under different initial pH values from 2000 to 2024.

4.4. Concentration of Supplied Electrolyte

Oil emulsion has poor electrical conductivity due to the lack of net charged ions in the solution. However, electrocoagulation requires a certain level of minimum conductivity for the flow of electrical current to occur. To enhance the electrical conductivity of the electrolyte, supporting electrolyte could be added to the oil emulsion. According to a study [35], supporting electrolytes can promote the conductivity of the electrolyte solution by reducing the passivation process at the anode, which enhances the current efficiency during electrocoagulation treatment. Moreover, the negative ions from the supporting electrolyte enhance the anodic dissolution process via localised pitting and produce more metal ions for the formation of metal coagulant [40]. If chloride-based compound is used as the supporting electrolyte, the chloride ions from such supporting electrolyte would produce chlorine, hypochlorous acid and hypochlorite ions as shown in Equations (2), (3) and (4), which aid in oxidising organic compounds and improving pollutants removal percentage [15]. Research on dairy industry wastewater [40] revealed that 97% and 92% of oil and chemical oxygen demand (COD) removal were achieved with 1.5 g/L of potassium chloride (KCl). Similarly, 1.5 g/L of sodium chloride (NaCl) was sufficient to treat egg processing wastewater, which yielded 89% COD removal [15].

$$2\mathrm{Cl}^- \rightarrow \mathrm{Cl}_2 + 2e^- \tag{2}$$

$$\mathrm{Cl}_2 + \mathrm{H}_2\mathrm{O} \rightarrow \mathrm{HOCl} + \mathrm{H}^+ + \mathrm{Cl}^- \tag{3}$$

$$\mathrm{HOCl} \rightarrow \mathrm{OCl}^- + \mathrm{H}^+ \tag{4}$$

However, excess supporting electrolyte can reduce the efficiency of electrocoagulation treatment. This is due to the buildup of strong ionic strength between Al^{3+} ions and supporting electrolyte, which weakens the diffusivity and activity of the Al^{3+} ions in the electrolyte. This could lead to lower generation of metal coagulant for the removal of emulsified oil [35]. Subsequently, excess salt would contribute to the formation of metal complex such as $AlCl_4^-$, which contributes to the dissolution process of the metal species and decreased available metal ion for the coagulant formation [40]. An example of common supporting electrolyte is sodium chloride, which is known for its cost-effectiveness and comparable efficiency in pollutant removal.

4.5. Voltage

Another factor affecting electrocoagulation treatment is the applied voltage (V). Applied voltage governs the reactions occurring at the electrodes, which includes anodic dissolution, coagulant formation, cathodic effervescent, and size of flocs [41,42]. In accordance with Faraday's Law (Equation (1)), the dissolution rate of the anode depends on the time and quantity of electrical current density supplied to the system [13,43]. However, as defined in Ohm's law (Equation (5)), V are proportional to current (A), I, and inversely proportional to resistance (R). This indicates that the amount of voltage applied to the system equals to the amount of current flowing through the electrolyte [44]. Therefore, an increment in voltage also increases the amount of metal ions oxidised from the anode, which contributes to the formation of metal coagulant for pollutant removal.

$$U = IR \tag{5}$$

Furthermore, increasing the voltage also induces the production of hydrogen gas at the cathode. This enhances the flux of dissolved gases on the electrode's surface, which increases the concentration of dissolved gases in the diffusion layer. This leads to a shorter nucleation time and favours smaller bubbles formation [45]. The density of bubbles produced increases, hence reducing the size of the bubbles [43]. This enhances the upwards flux and sludge formation for a more effective pollutant removal process [13].

A similar trend was observed for the treatment of wastewater from the dairy industry [46]. As the applied voltage increased from 10 V to 60 V, the removal percentage of COD, BOD and TSS increased from 60.6% to 98.8%, 57.9% to 98%, and 49.29% to 97.75%, respectively. In addition, maximum bacterial removal of >99.9% was also achieved at 60 V.

Table 1 summarises the removal percentage of electrocoagulation treatment under different applied voltages. It can be observed that high removal percentage in electrocoagulation treatment can be obtained despite different intensity level of voltage applied. This occurs due to the different characteristic of each wastewater. From the reviewed articles, it can be observed that the voltages applied ranged from 9 V to 60 V. Higher intensity of voltage applied could lead to higher energy consumption and operation costs, which are not conducive for the adoption of electrocoagulation treatment, from economic perspective. In fact, it might also result in less efficient electrocoagulation treatment [44]. This is caused by the high rate of hydrogen gas formation that breaks the flocs and simultaneously jeopardises the adsorption process for pollutant removal. On the other hand, high voltage may also induce side reactions such as charge reversal of the colloids by excess coagulant, dissolution of coagulants formed and expedited formation of passivation films on the surface of the electrode [47].

4.6. Initial Oil Concentration

The characteristics of wastewater, particularly pollutant concentration, fundamentally determine treatment requirements. In this context, initial oil concentration is one of the elements considered in the characterising the wastewater. Very high initial oil concentration in wastewater could significantly reduce the effectiveness of the electrocoagulation treatment. The removal of oil pollutants is dependent on the flow of current throughout the treatment system to produce metal ions, metal hydroxide coagulants and hydrogen bubbles. However, oil is a poor conductor of electricity. High concentration of oil increases the resistance of the electrolyte and reduces the conductivity of current between the electrodes. Thus, the accumulated resistance limits the flow of current through the electrolyte and limits the production of essential elements for oil removal.

Similarly, at constant current density, supporting electrolyte and pH parameter settings, the amount of metal coagulant produced in the electrolyte is the limiting factor for electrocoagulation treatment process. Under the same parameter settings, the amount of metal hydroxide coagulant produced is fixed [18]. When the initial oil concentration of the electrolyte increases, the removal capacity of electrocoagulation treatment is reduced. Therefore, this renders electrocoagulation treatment less effective at high initial oil concentration.

A comparison of the efficiency of electrocoagulation treatment on different types of street food was conducted by Shokri and Fard [9]. The study showed that the efficiency of electrocoagulation treatment was slightly reduced when treating Hainanese chicken rice vendor's wastewater, which has a higher content of oil pollutants, at 310 mg/L ± 12%, compared to noodles and dumplings vendor's wastewater with a lower concentration of oil pollutants of at 178 mg/L ± 8%. Another study [18] also reported a similar trend, showing decline in the effectiveness of electrocoagulation treatment from 94.6% to 82.3% when the initial COD concentration increased from 1000 mg/L to 4000 mg/L.

Having established the technical parameters and performance characteristics of electrocoagulation, which demonstrate the technical viability of this technology for food wastewater treatment across diverse industrial applications, the following section examines the commercial and technological development trends through patent landscape analysis. While the patent search was not restricted to the food industry, the analysis provides valuable context for food industry adoption. It reveals the progress of electrocoagulation technology and potentially adaptable innovations for food wastewater, thereby providing insights into its practical implementation and industrial adoption.

Table 1. Removal percentage achieved from electrocoagulation treatment under different applied voltage.

Sample	Voltage Applied	Removal Percentage	Reference
Pond Water	12 V	66% Turbidity removal	[48]
River Water		98% Turbidity removal	
Water	15 V	60-70% Hardness removal 91% Fluoride removal	[42]
Tanning Industry	9 V	89% COD removal 83% Chromium removal 85% TDS removal	[44]
Urban Runoff	30 V	80% COD removal 82% BOD removal 92% Turbidity removal	[41]
Textile Industry	30 V	87% COD removal 91% TSS removal 98% Dye removal	[43]
Dairy Industry	60 V	98.84% COD removal 97.95% BOD removal 97.75% TSS removal >99.9% Bacterial removal	[46]

5. Patent Analysis for Electrocoagulation in Wastewater Treatment (2014-2024)

5.1. Patent Overview from 2014 to 2024

Based on Figure 7, which depicts trend based on data obtained from Lens.org, the total number of patents from 2014 to 2024 was 868 patents (608 patent applications and 270 patents granted). Such a high number of patent applications and granted patents imply that the application of electrocoagulation in wastewater treatment is becoming an emerging technology that is highly patentable. In general, there are four trends that can be identified from Figure 7. These include a decrease in patents published from 2014 to the lowest point in 2016, a spike in published patents from 2017 to the peak in 2019, a slight dip from 2020-2021, and a gradual increase in published patents until 2024. Each trend would be analysed to understand the direction of electrocoagulation patenting.

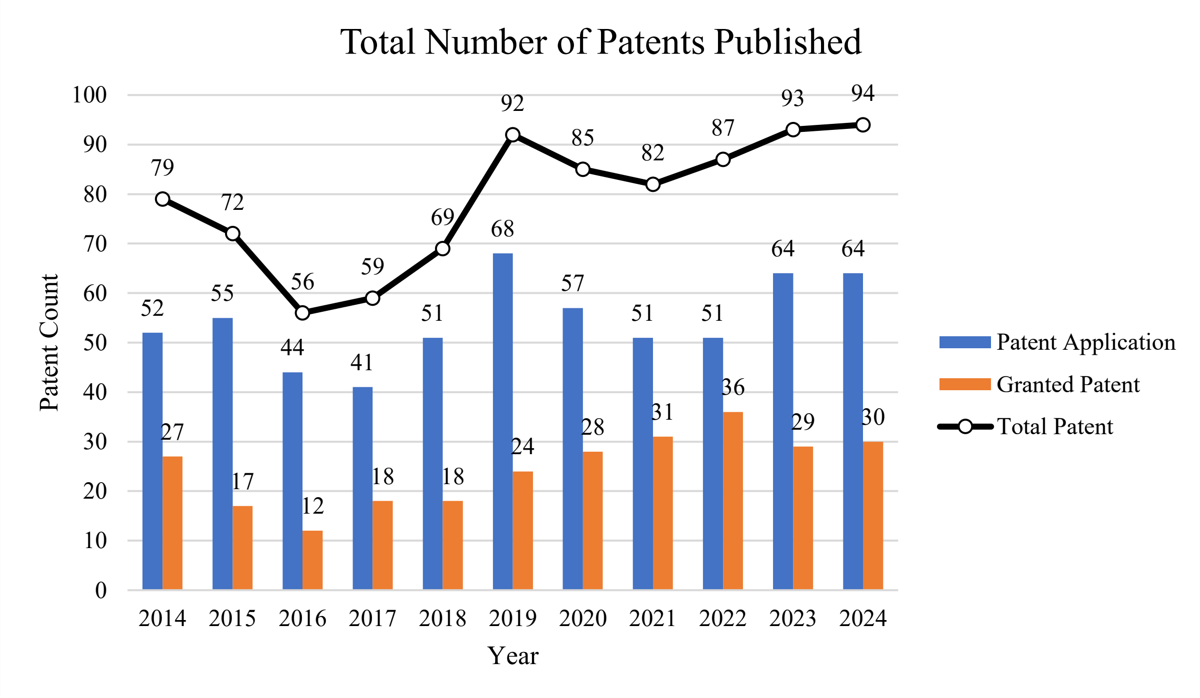

Figure 7. Total patents published in period from 2014 to 2024 (according to data from Lens.org) [Accessed on 7th May 2025].

In 2014, the total patents were 79 (52 patent applications and 27 granted patents), which then decreased to 72 (55 patent applications and 17 granted patents) in the following year. The total number of patents further decreased over the next year until it reaching the lowest point of the decade. In 2016, only 56 patents were published (44 patent applications and 12 granted patents). This could possibly reflect the slow emergence of interest in applying electrocoagulation to wastewater treatment. Another possibility is that the research was not ready for patenting. The number of patents applied gradually increased over the following three years (2017-2019). The number of patents published in 2019 showed a significant increase to 92 published patents (68 patent applications and 24 granted patents). This increase in patents published suggests renewed interest in electrocoagulation applications for wastewater treatment. Similarly, the increase in the number of granted patents also indicates growing technological innovations that are patentable.

However, the following two years saw a drop in total patents published, with 85 published patents (57 patent applications and 28 granted patents) in 2020 and 82 published patents (51 patent applications and 31 granted patents) in 2021. This decline may be due to the impact of COVID-19 pandemic, which affected many research activities throughout the world and may have delayed the patenting process. It is important to note that the number of granted patents continued to increase steadily despite the decreased total published patents in 2020 and 2021. This increase suggests enhanced innovation levels in electrocoagulation for wastewater treatment that are suitable for patenting. This trend continued until it reached the decade peak of 36 granted patents in 2022. In the same year, the total published patents also increased until reaching the decade peak of 94 published patents (64 patent applications and 30 granted patents) in 2024. This growth trajectory in patent publications reflects increased commercial interest. To better understand the driving forces behind this trend, it is essential to examine the key players in this technological landscape.

5.2. Patent Jurisdiction

Finally, analysing patents from various countries that have patented technologies related to electrocoagulation in wastewater treatment is important for understanding technological focuses around the world. Such data are also important for helping companies and researchers to determine the future regions or continents that will play important roles in the development of electrocoagulation technology. Figure 8 depicts the patent document counts from various jurisdictions in the field of electrocoagulation in wastewater treatment.

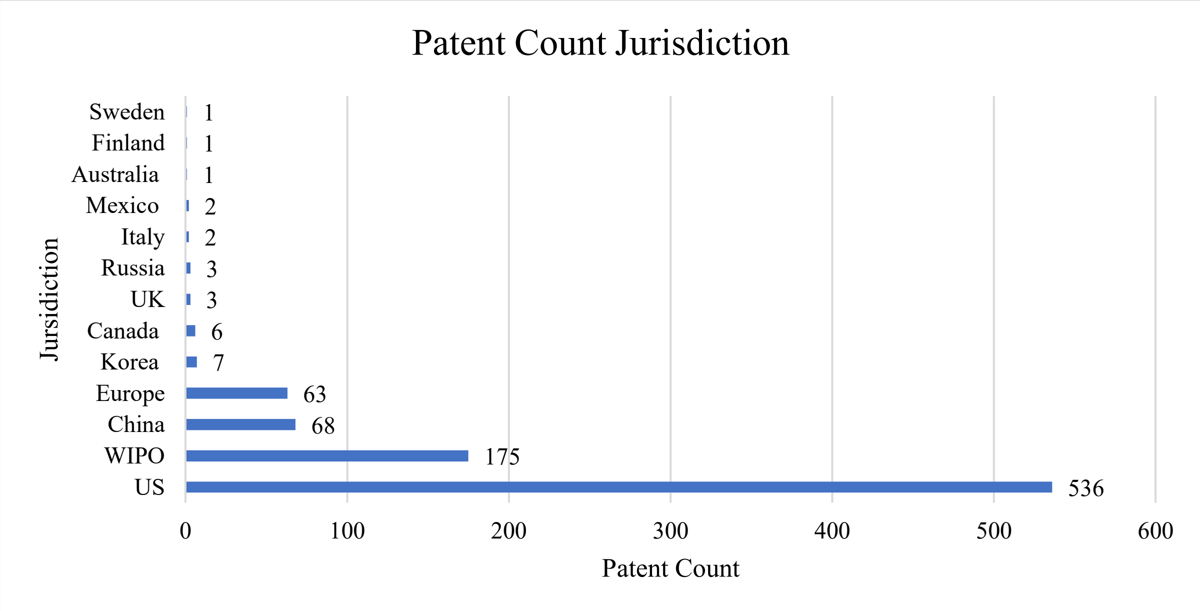

Figure 8. Patent count according to jurisdiction from 2014-2024 (Lens.org) [Accessed on 7th May 2025].

The United States of America (USA) serves as the main source of patent activities related to electrocoagulation in wastewater treatment. With 536 related patent documents over the decade, it is not surprising that the USA achieved such numbers. This is due to its strong economic and research infrastructure that encourages research activities and subsequently advances electrocoagulation technology. Industrial players and research institutes in America with strong fundamental knowledge and background knowledge related to wastewater treatment were able to successfully patent various technological improvements for electrocoagulation.

After the USA, the World Intellectual Property Organisation (WIPO) recorded 175 filed patent documents. WIPO serves as the primary intellectual property promotion and protection agency worldwide. This substantial number of patent documents suggests global interest in promoting and protecting various technological applications and advancements in electrocoagulation. In addition, it indicated that there has been a surge in global interest in applying electrocoagulation to wastewater treatment due to the patenting of such technologies in various countries. Through WIPO, the patents are protected and serve as an initiative to promote electrocoagulation technology globally.

In the Asian region, the main players in patenting electrocoagulation technology are China (68 patent documents) and the Republic of Korea (7 patent documents). The high number of patent documents in both countries indicates increased interest in applying electrocoagulation to treatment of wastewater. China is well positioned to focus on wastewater treatment due to its massive industrial activities. In 2016, China released the "13th Five Year Plan" which details the need for 30% water reclamation around the Beijing area by the end of 2020 [51]. This incentivised the need to improve or advance current wastewater treatment technologies. Thus, this explains the high number of patent documents compared to Korea.

Europe also serves as a leader in patenting of electrocoagulation technologies, with 63 patent documents. The high number of patent documents filed in Europe suggests emerging interest in the region in electrocoagulation technology too. This is consistent with the circular economy action plan developed by the European Union (EU) to reduce environmental damage. The "WIDER UPTAKE" initiative undertaken by the EU in 2021 [52] has furthered the application of electrocoagulation in wastewater treatment. The collaboration between the EU and China under the "China-Europe Water Platform" (CEWP) has also advanced researches in wastewater treatment. This could partially explain the similar amount of patent documents filed between both jurisdictions.

Despite the prevalence of patent documents in the main economic regions of the world, there were still some other countries involved in patenting electrocoagulation for wastewater treatment documents. For example, Canada has six patent related documents. Subsequently, one of the top applicants was a company located in Canada. Other European countries such as the United Kingdom (3), Italy (2), Russia (3), Finland (1) and Sweden (1) also have filed patent documents. These low numbers of patent documents suggest that interest in electrocoagulation technology leans towards academic research instead of commercial purposes. Other jurisdictions such as Mexico (2 patent documents) and Australia (1 patent document) may also have a similar trend that is more academically focused instead of commercially oriented.

While a high volume of patents exists across all sectors, few explicitly target food industry wastewater. The search was intentionally broad because patents are typically drafted to cover multiple industries rather than a single sector. Consequently, food-specific patents cannot be reliably isolated from the search, and the patent trends presented here reflect general commercial interest rather than food-focused developments. Overall, while the patent landscape demonstrates sustained technological development in electrocoagulation, the translation from laboratory research and patent activity to large scale industrial implementation remains constrained by several challenges that must be addressed to fully realise the commercial potential demonstrated in the patent landscape.

6. Challenges and Prospects

6.1. Scalability and System Complexity

Although electrocoagulation has been widely recognised as a promising technology for oily wastewater treatment, several challenges remain that hinder its large-scale adoption in food industries. A critical issue lies in the scalability of electrocoagulation systems. Most studies reported in the literature are limited to laboratory-scale or batch experiments [6,9,11]. While these studies demonstrate high removal efficiencies for oil and COD, the translation of results into continuous-flow or industrial-scale operations remains limited [18,22]. Moreover, wastewater characteristics in real food industry effluents are highly complex, containing organic matter, nutrients, and emulsified oil fractions that behave differently compared to synthetic wastewater [34,59]. This discrepancy highlights the need for more robust and scalable systems that can handle variable pollutant loads without compromising performance.

6.2. Electrode Passivation

Another significant challenge is electrode passivation, which reduces efficiency over time due to the formation of insulating oxide layers on the electrode surface [6,11,35]. Passivation increases internal resistance, lowering current efficiency and pollutant removal. Frequent electrode replacement adds to the operational cost, raising concerns regarding long-term economic feasibility. Although approaches such as polarity reversal and hybrid electrode materials have been proposed, their effectiveness still requires validation at the industrial scale [59,60].

6.3. Energy Consumption

Energy consumption is another major barrier. Studies show that energy and electrode costs account for about 60% of the total operating costs of electrocoagulation [6,9,11]. While increasing applied voltage improves pollutant removal, excessive voltage leads to higher energy demand and can destabilise the process by breaking flocs or inducing side reactions [41–44]. Optimisation is thus critical. Fotovat and Hosseini [53] demonstrated that energy consumption could be reduced by 37% with optimised residence time while maintaining oil removal efficiency above 98%. However, efficiency remains highly dependent on operational parameters such as electrode type, pH, initial oil concentration, and electrolyte composition, which complicates standardisation for industrial applications [40–64].

6.4. Operation Parameters Dependencies

Electrode selection, commonly aluminium and iron, is yet another challenge that significantly affects coagulant formation and energy requirements. For instance, aluminium shows faster coagulant production, whereas iron has slower dissolution and higher energy demand [60]. Similarly, electrolysis time plays a critical role impacting the process economy. Although pollutant removal generally increases with reaction time, once optimal conditions are reached (20–30 min), extending time adds little benefit while raising energy costs [62]. pH sensitivity further complicates treatment, as performance is highest near neutral pH (6.5–7), but less effective under acidic or basic conditions due to unfavourable species formation [61].

In addition, initial oil concentration strongly influences conductivity, whereby high oil loads reducing the current flow and lower the pollutant removal [62]. On the other hand, the use of supporting electrolytes such as NaCl can enhance conductivity and improve pollutant removal [32], but excessive concentrations reduce the efficiency due to ionic strength effects and complex formation [63]. Finally, applied voltage directly influences pollutant removal, bubble formation, and sludge characteristics. However, excessively high voltages increase energy costs [53] and may reduce treatment efficiency [32]. These dependencies underline the challenge of optimising electrocoagulation process for diverse real-world wastewater streams.

6.5. Sludge Management

The management of sludge by-products also poses difficulties. Although electrocoagulation generates up to 60% less sludge than chemical coagulation, the by-products still require proper handling [7,8]. The sludge typically contains a mixture of metal hydroxides and organic matter, raising concerns about safe disposal [11]. Valorisation strategies have been suggested, such as metal recovery, biogas generation via anaerobic digestion, or the use of sludge in construction materials [54,57,58,60]. Such approaches align with circular economy principles, turning waste into valuable resources while improving environmental sustainability.

6.6. Prospects of Artificial Intelligence and Machine Learning

To overcome the conventional challenges for electrocoagulation technology, the integration of Artificial Intelligence (AI) and Machine Learning (ML) represents a transformative opportunity for advancing electrocoagulation. Traditional process design often relies on empirical optimisation, which is time-consuming and limited in capturing nonlinear, multivariate interactions in complex wastewater systems [59,60]. AI-based approaches, including artificial neural networks (ANNs), support vector machines (SVMs), and random forest models, have been successfully applied to predict EC performance and optimise operating conditions [17,61]. For example, El Jery et al. [65] applied ANNs to model oil industry wastewater treatment, demonstrating reliable prediction of COD removal efficiency under varying current densities and operating times.

ML-driven frameworks also enable multi-objective optimisation, balancing trade-offs between pollutant removal, energy consumption, and sludge generation [7,60]. Shahedi et al. [61] highlighted that AI integration into industrial EC operations allows dynamic adjustment of parameters in real time, ensuring consistent performance under variable effluent conditions. Similarly, Tahreen et al. [62] noted that AI-supported optimisation frameworks could stabilise treatment efficiency under fluctuating pollutant loads, a critical factor for industrial scalability.

In addition to process optimisation, AI supports predictive maintenance and fault detection. By analysing sensor data streams from EC reactors, machine learning models can detect early signs of electrode passivation, scaling, or irregular conductivity before they compromise efficiency [33]. This predictive capability reduces downtime and operational costs while extending electrode lifespan. The convergence of AI with Industry 4.0 technologies—including IoT, smart sensors, cloud computing, and digital twins—further enables real-time monitoring, remote control, and autonomous decision-making in EC systems [55,56,63].

The integration of renewable energy sources offers a promising pathway to reduce both the operational costs and carbon footprint of electrocoagulation systems [54]. Combined with Industry 4.0 technologies, such as IoT and digital twins, real-time optimisation, predictive maintenance, and intelligent energy management [55,56,61] become increasingly achievable. AI-driven control systems could stabilise treatment performance even under fluctuating wastewater conditions, addressing some of the operational uncertainties that currently hinder industrial uptake.

6.7. Prospects of Life Cycle Assessment and Techno-economic Analysis

Beyond process-level optimisation, a broader evaluation of electrocoagulation through life cycle assessment (LCA) and techno-economic analysis (TEA) is essential to benchmark its environmental and economic performance against alternative wastewater treatment technologies [54,57,58]. Pilot-scale demonstrations under continuous-flow conditions remain essential to evaluate technical feasibility, economic performance, and environmental impact in real-world scenarios. Strong collaboration between academia, industry, and policymakers will be vital to accelerate the transition of electrocoagulation from laboratory-scale research into a commercially viable, AI-enhanced, and sustainable technology for food wastewater treatment [7,33,59–63].

7. Conclusions

Wastewater treatment is an important aspect in maintaining global water security, with edible oils among the most challenging pollutants requiring specialised removal strategies. One of the methods under purview is electrocoagulation. Electrocoagulation has emerged as a potential solution based on reported high removal efficiency, reduced chemical demand, and comparatively lower sludge generation. Numerous studies have demonstrated that process efficiency is influenced by factors such as electrode material, treatment duration, and applied voltage. A bibliometric survey of Scopus-indexed literature from 2000 to 2024 indicates a consistent increase in publications, with a marked surge in recent years: between 2020 and 2024, 17 related manuscripts were published, surpassing the cumulative output from the preceding two decades (2000-2019). It should be noted that the findings presented here are trend-based insights drawn from a scoping review, rather than statistically validated conclusions. This trend suggests the growing research attention towards electrocoagulation for oily wastewater treatment. A broad patent landscape analysis for the past decade from 2014 to 2024 in all industrial sectors further points to rising global interest in commercialising this technology. Patent activity steadily increased between 2014 and 2019, with a temporary decline from 2020 to 2022 likely attributable to research and development disruptions during the COVID-19 pandemic. The leading patent applicants reflect the multidisciplinary nature of the field, with strong contributions from both academia and industry: Massachusetts Institute of Technology (22 patents), Gradiant Corporation (20 patents), as well as petroleum-sector (Rockwater Resources LLC) and electrical-sector (Daikin Industries Ltd.) companies. These observations suggest diverse industrial relevance and potential innovation pathways for electrocoagulation. Despite these advances, several challenges hinder large-scale adoption, including electrode passivation, high energy requirements, and by-product (sludge) management. To accelerate commercialisation, future work should prioritise pilot-scale demonstrations, integration of renewable energy and artificial intelligence for process optimisation, life-cycle and techno-economic assessments, and exploration of sludge valorisation strategies. Overall, the trends observed in this review suggest that electrocoagulation holds strong potential as an effective and viable technology for oily food wastewater treatment. It should be noted that the findings presented here are trend-based insights drawn from a scoping review, rather than statistically validated conclusions. An extended quantitative meta-analysis would allow more robust conclusions to be drawn. Nonetheless, this review demonstrates that electrocoagulation is a promising and increasingly relevant technology, and the growing body of research and patent activity points toward its continued advancement for effective food wastewater management.

Acknowledgements

This work was financially supported by Universiti Teknologi Malaysia [UTM DiR Grant PY/2024/00454].

Declaration of Conflict of Interest

The authors declared no conflict of interest with any other party on the publication of the current work.

ORCID

Lian See Tan https://orcid.org/0000-0001-9039-7926
Noor Fazliani Shoparwe https://orcid.org/0000-0002-4329-2459
Mohamed Mahmoud El-Sayed Nasef https://orcid.org/0000-0002-0192-5107
Sinung Suakanto https://orcid.org/0000-0001-8071-4473

References

[1] MarketsandMarkets, Edible Oils Market Worth $268.9 Billion by 2027 - Exclusive Report by MarketsandMarketsTM. Cision PR Newswire (2023). https://www.prnewswire.com/news-releases/edible-oils-market-worth-268-9-billion-by-2027--exclusive-report-by-marketsandmarkets-301752780.html (accessed 13 May 2026).

[2] D. Robinson, Water Pollution: Causes and Solutions. Earth.org (2022). https://earth.org/what-are-the-causes-of-water-pollution/ (accessed 4 May 2026).

[3] J. Ma, X. Fu, W. Xia, R. Zhang, K. Fu, G. Wu, B. Jia, S. Li, and J. Li, Removal of Emulsified Oil from Water by Using Recyclable Chitosan Based Covalently Bonded Composite Magnetic Flocculant: Performance and Mechanism. Journal of Hazardous Materials 419 (2021) 126529. https://doi.org/10.1016/j.jhazmat.2021.126529.

[4] E. Yonguep, K.F. Kapiamba, K.J. Kabamba, and M. Chowdhury, Formation, Stabilization and Chemical Demulsification of Crude Oil-in-Water Emulsions: A Review. Petroleum Research 7 (2022) 459–472. https://doi.org/10.1016/j.ptlrs.2022.01.007.

[5] A. Genc, and B. Bakirci, Destabilization and Treatment of Emulsified Oils in Wastewaters by Electrocoagulation. Water Environment Research: A Research Publication of the Water Environment Federation 88 (2016) 2008–2014. https://doi.org/10.2175/106143016X14733681695203.

[6] A. Kadier, Z. Al-Qodah, G.K. Akkaya, D. Song, J.M. Peralta-Hernández, J.-Y. Wang, C. Phalakornkule, M. Bajpai, N.M. Niza, V. Gilhotra, M.E. Bote, Q. Ma, C.C. Obi, and C.A. Igwegbe, A State-of-the-Art Review on Electrocoagulation (EC): An Efficient, Emerging, and Green Technology for Oil Elimination from Oil and Gas Industrial Wastewater Streams. Case Studies in Chemical and Environmental Engineering 6 (2022) 100274. https://doi.org/10.1016/j.cscee.2022.100274.

[7] D. Syam Babu, T.S. Anantha Singh, P.V. Nidheesh, and M. Suresh Kumar, Industrial Wastewater Treatment by Electrocoagulation Process. Separation Science and Technology 55 (2020) 3195–3227. https://doi.org/10.1080/01496395.2019.1671866.

[8] N. Chawaloesphosiya, J. Mongkolnauwarat, C. Prommajun, K. Wongwailikhit, and P. Painmanakul, Treatment of Cutting-Oily Wastewater by Electrocoagulation-Flotation (ECF) Process: Modeling Approach. Environmental Engineering Research 20 (2015) 392–396. https://doi.org/10.4491/eer.2015.085.

[9] A. Shokri, and M.S. Fard, A Critical Review in Electrocoagulation Technology Applied for Oil Removal in Industrial Wastewater. Chemosphere 288 (2022) 132355. https://doi.org/10.1016/j.chemosphere.2021.132355.

[10] M.A. Jasim, and F. Yasir Al Jaberi, Treatment of Oily Wastewater by Electrocoagulation Technology: A General Review (2018-2022): Review Paper. Journal of Electrochemical Science and Engineering 13(2) (2022) 361–372. https://doi.org/10.5599/jese.1472.

[11] H. Muvel, M.K. Jindal, P.K. Tewari, and V. Anand, Advancements in Electrocoagulation for Oily Wastewater Treatment: Mechanisms, Efficiency, and Applications. Journal of Water Process Engineering 68 (2024) 106291. https://doi.org/10.1016/j.jwpe.2024.106291.

[12] P. Drogui, M. Asselin, S.K. Brar, H. Benmoussa, and J.-F. Blais, Electrochemical Removal of Pollutants from Agro-Industry Wastewaters. Separation and Purification Technology 61 (2008) 301–310. https://doi.org/10.1016/j.seppur.2007.10.013.

[13] M. Kobya, and S. Delipinar, Treatment of the Baker's Yeast Wastewater by Electrocoagulation. Journal of Hazardous Materials 154 (2008) 1133–1140. https://doi.org/10.1016/j.jhazmat.2007.11.019.

[14] W. Qasim, and A.V. Mane, Characterization and Treatment of Selected Food Industrial Effluents by Coagulation and Adsorption Techniques. Water Resources and Industry 4 (2013) 1–12. https://doi.org/10.1016/j.wri.2013.09.005.

[15] R. Sridhar, V. Sivakumar, J. Prakash Maran, and K. Thirugnanasambandham, Influence of Operating Parameters on Treatment of Egg Processing Effluent by Electrocoagulation Process. International Journal of Environmental Science and Technology 11 (2014) 1619–1630. https://doi.org/10.1007/s13762-013-0301-5.

[16] M. Ji, X. Jiang, and F. Wang, A Mechanistic Approach and Response Surface Optimization of the Removal of Oil and Grease from Restaurant Wastewater by Electrocoagulation and Electroflotation. Desalination and Water Treatment 55 (2015) 2044–2052. https://doi.org/10.1080/19443994.2014.929034.

[17] H. Ates, N. Dizge, and H.C. Yatmaz, Combined Process of Electrocoagulation and Photocatalytic Degradation for the Treatment of Olive Washing Wastewater. Water Science and Technology: A Journal of the International Association on Water Pollution Research 75 (2017) 141–154. https://doi.org/10.2166/wst.2016.498.

[18] A. Mirshafiee, A. Rezaee, and R.S. Mamoory, A Clean Production Process for Edible Oil Removal from Wastewater Using an Electroflotation with Horizontal Arrangement of Mesh Electrodes. Journal of Cleaner Production 198 (2018) 71–79. https://doi.org/10.1016/j.jclepro.2018.06.201.

[19] K. Sardari, J. Askegaard, Y.-H. Chiao, S. Darvishmanesh, M. Kamaz, and S.R. Wickramasinghe, Electrocoagulation Followed by Ultrafiltration for Treating Poultry Processing Wastewater. Journal of Environmental Chemical Engineering 6 (2018) 4937–4944. https://doi.org/10.1016/j.jece.2018.07.022.

[20] G. Varank, S. Yazici Guvenc, and A. Demir, A Comparative Study of Electrocoagulation and Electro-Fenton for Food Industry Wastewater Treatment: Multiple Response Optimization and Cost Analysis. Separation Science and Technology 53 (2018) 2727–2740. https://doi.org/10.1080/01496395.2018.1470643.

[21] S. Veli, L. Ozbay, B. Ozbay, A. Arslan, and E. Cebi, Optimization of Process Variables for Treatment of Food Industry Effluents by Electrocoagulation. Global NEST Journal 20 (2018) 551–557. https://doi.org/10.30955/gnj.002640.

[22] S. Yılmaz, E.E. Gerek, Y. Yavuz, and A.S. Koparal, Treatment of Vinegar Industry Wastewater by Electrocoagulation with Monopolar Aluminum and Iron Electrodes and Toxicity Evaluation. Water Science and Technology: A Journal of the International Association on Water Pollution Research 78 (2018) 2542–2552. https://doi.org/10.2166/wst.2019.013.

[23] R. Niazmand, M. Jahani, and S. Kalantarian, Treatment of Olive Processing Wastewater by Electrocoagulation: An Effectiveness and Economic Assessment. Journal of Environmental Management 248 (2019) 109262. https://doi.org/10.1016/j.jenvman.2019.109262.

[24] A. Temitope Adegoke, and E. Temitayo Abayomi, A Preliminary Study on the Treatment of Restaurant Wastewater Using Electrocoagulation Technique. Journal of Degraded and Mining Lands Management 7 (2020) 2029–2033. https://doi.org/10.15243/jdmlm.2020.072.2029.

[25] K. H. El-Ezaby, M. I. El-Gammal, A. Y. Shaaban, Electrocoagulation treatment for wastewaters from some restaurants in New Damietta City-Egypt, Journal of Environmental Sciences, 49 (2020) 87–98. https://doi.org/10.21608/joese.2020.177139

[26] Y.D. Shahamat, M.R. Khani, H. Mahdizadeh, K. Kannan, L.R. Kalankesh, B. Kamarehei, and M.M. Baneshi, Olive Mill Wastewater (Omw) Treatment by Hybrid Processes of Electrocoagulation/Catalytic Ozonation and Biodegradation. Environmental Engineering and Management Journal 19 (2020) 1401–1410. https://doi.org/10.30638/eemj.2020.130.

[27] P.V. Ngobeni, L. Gutu, M. Basitere, T. Harding, and D. Ikumi, Poultry Slaughterhouse Wastewater Treatment Using an Integrated Biological and Electrocoagulation Treatment System: Process Optimisation Using Response Surface Methodology. Sustainability 14 (2022) 9561. https://doi.org/10.3390/su14159561.

[28] M. C. Potrich, E. D. S. A. Duarte, M. D. S. Sikora, R. D. Costa da Rocha, Electrocoagulation for nutrients removal in the slaughterhouse wastewater: comparison between iron and aluminum electrodes treatment, Environmental Technology 43 (2022) 751–765. https://doi.org/10.1080/09593330.2020.1804464.

[29] M.C. Potrich, E. de S.A. Duarte, M. de S. Sikora, and R.D. Costa da Rocha, Electrocoagulation for Nutrients Removal in the Slaughterhouse Wastewater: Comparison between Iron and Aluminum Electrodes Treatment. Environmental Technology 43 (2022) 751–765. https://doi.org/10.1080/09593330.2020.1804464.

[30] S. Elia, M. Stylianou, and A. Agapiou, Combined EC/EO Processes for Treating Goat Cheese Whey Wastewater. Sustainable Chemistry and Pharmacy 32 (2023) 100963. https://doi.org/10.1016/j.scp.2022.100963.

[31] A. Şen, C. Akarsu, Z. Bilici, H. Arslan, and N. Dizge, Treatment of Tomato Paste Wastewater by Electrochemical and Membrane Processes: Process Optimization and Cost Calculation. Water Science and Technology: A Journal of the International Association on Water Pollution Research 89 (2024) 1879–1890. https://doi.org/10.2166/wst.2024.079.

[32] J.A.L. Soo, N.F. Shoparwe, L.S. Tan, P.L. Kiew, A.K. Nurulbahiyah, and Y.F. Yeong, Electrochemical and Kinetic Insights into Waste Cooking Oil Removal via Electrocoagulation: Parameter Interactions and Mechanism Elucidation. International Journal of Environmental Science and Technology 22 (2025) 12295–12306. https://doi.org/10.1007/s13762-025-06428-y.

[33] C. An, G. Huang, Y. Yao, and S. Zhao, Emerging Usage of Electrocoagulation Technology for Oil Removal from Wastewater: A Review. The Science of the Total Environment 579 (2017) 537–556. https://doi.org/10.1016/j.scitotenv.2016.11.062.

[34] H. Asgharnejad, E. Khorshidi Nazloo, M. Madani Larijani, N. Hajinajaf, and H. Rashidi, Comprehensive Review of Water Management and Wastewater Treatment in Food Processing Industries in the Framework of Water-Food-Environment Nexus. Comprehensive Reviews in Food Science and Food Safety 20 (2021) 4779–4815. https://doi.org/10.1111/1541-4337.12782.

[35] A.Y. Kilany, S.A. Nosier, M. Hussein, M.H. Abdel-Aziz, and G.H. Sedahmed, Combined Oil Demulsification and Copper Removal from Copper Plating Plant Effluents by Electrocoagulation in a New Cell Design. Separation and Purification Technology 248 (2020) 117056. https://doi.org/10.1016/j.seppur.2020.117056.

[36] R. Daghrir, P. Drogui, J. François Blais, and G. Mercier, Hybrid Process Combining Electrocoagulation and Electro-Oxidation Processes for the Treatment of Restaurant

Wastewaters. Journal of Environmental Engineering 138 (2012) 1146–1156. https://doi.org/10.1061/(asce)ee.1943-7870.0000579.

[37] T.J. Mohammed, and H.A. Al-Zuheri, Enhancing Oily Wastewater Treatment in Petroleum Industry Using Magnetite Nanoparticles. Arabian Journal for Science and Engineering 45 (2020) 7573–7585. https://doi.org/10.1007/s13369-020-04713-1.

[38] P.P. Das, Anweshan, and M.K. Purkait, Treatment of Cold Rolling Mill (CRM) Effluent of Steel Industry. Separation and Purification Technology 274 (2021) 119083. https://doi.org/10.1016/j.seppur.2021.119083.

[39] O. Chavalparit, and M. Ongwandee, Optimizing Electrocoagulation Process for the Treatment of Biodiesel Wastewater Using Response Surface Methodology. Journal of Environmental Sciences (China) 21 (2009) 1491–1496. https://doi.org/10.1016/s1001-0742(08)62445-6.

[40] A. Aitbara, M. Cherifi, S. Hazourli, and J.-P. Leclerc, Continuous Treatment of Industrial Dairy Effluent by Electrocoagulation Using Aluminum Electrodes. Desalination and Water Treatment 57 (2016) 3395–3404. https://doi.org/10.1080/19443994.2014.989411.

[41] M. Afsharnia, and M. Saeidi, Evaluating the Effectiveness of Electrocoagulation (EC) Process in Reducing the COD of Simulated Urban Runoffs. International Journal of Electrochemical Science 13 (2018) 5172–5183. https://doi.org/10.20964/2018.06.08.

[42] P. Mahammedrafi, An experimental study of electrocoagulation process applied for influence of fluoride ions on hardness removal, International Journal of Engineering Research and Application 8 (2018) 33–38. https://www.ijera.com/papers/Vol8_issue2/Part-1/F0802013338.pdf .

[43] T. Shahriari, and B. Saeb, Assessment of Effective Operational Parameters on Dyeing Wastewater Treatment by Electrocoagulation Process. Pollution 3(3) (2017) 517–526.

[44] H. Setyawati, D. Galuh, and E. Yunita, Effect of Electrode Distance and Voltage on CR, COD, and TSS Reduction in Waste Water Tanning Industry using Electrocoagulator Batch. Journal of Sustainable Technology and Applied Science 2 (2021) 24–30. https://doi.org/10.36040/jstas.v2i1.3574.

[45] S.G. da Cruz, A.J.B. Dutra, and M.B.M. Monte, The Influence of Some Parameters on Bubble Average Diameter in an Electroflotation Cell by Laser Diffraction Method. Journal of Environmental Chemical Engineering 4 (2016) 3681–3687. https://doi.org/10.1016/j.jece.2016.05.017.

[46] D. Ankoliya, A. Mudgal, M.K. Sinha, V. Patel, and J. Patel, Application of Electrocoagulation Process for the Treatment of Dairy Wastewater: A Mini Review. Materials Today: Proceedings 77 (2023) 117–124. https://doi.org/10.1016/j.matpr.2022.10.254.

[47] S.O.A. Nassar, M.S. Yusoff, H. Halim, N.H. Mokhtar Kamal, M.J.K. Bashir, T.S.B.A. Manan, H.A. Aziz, and A. Mojiri, Ultrasonic (US)-Assisted Electrocoagulation (EC) Process for Oil and Grease (O&G) Removal from Restaurant Wastewater. Separations 10 (2023) 61. https://doi.org/10.3390/separations10010061.

[48] M. Masthura, The Effect of Applied Voltage in the Electrocoagulation Process of Reducing Pond and River Water Turbidity. Elkawnie: Journal of Islamic Science and Technology 6 (2020) 156. https://doi.org/10.22373/ekw.v6i1.5538.

[49] Electrochemical Disinfection. E2METRIX PFAS Solutions | Onsite PFAS Destruction (2025). https://e2metrix.com/products-solutions/ecothor/ (accessed 4 May 2026).

[50] Muddy Rivers Technologies Inc., Amprey, n.d. https://muddyriver.ca/solutions/amprey/ (accessed April 27, 2025)

[51] A. Xu, Y.-H. Wu, Z. Chen, G. Wu, Q. Wu, F. Ling, W.E. Huang, and H.-Y. Hu, Towards the New Era of Wastewater Treatment of China: Development History, Current Status, and Future Directions. Water Cycle 1 (2020) 80–87. https://doi.org/10.1016/j.watcyc.2020.06.004.

[52] A. Soo, and H.K. Shon, A Nutrient Circular Economy Framework for Wastewater Treatment Plants. Desalination 592 (2024) 118090. https://doi.org/10.1016/j.desal.2024.118090.

[53] F. Fotovat, and M. Hosseini, Treatment of Oily Wastewater by Electrocoagulation: Simultaneous Optimization of Oil Removal Efficiency and Specific Energy Consumption. Journal of Water Process Engineering 55 (2023) 104221. https://doi.org/10.1016/j.jwpe.2023.104221.

[54] A.Y. Çetinkaya, Integration of Electrocoagulation and Solar Energy for Sustainable Wastewater Treatment: A Thermodynamic and Life Cycle Assessment Study. Environmental Monitoring and Assessment 197 (2025) 224. https://doi.org/10.1007/s10661-025-13662-x.

[55] T.M. Olatunde, A.C. Okwandu, D.O. Akande, and Z.Q. Sikhakhane, Reviewing the Role of Artificial Intelligence in Energy Efficiency Optimization. Engineering Science & Technology Journal 5 (2024) 1243–1256. https://doi.org/10.51594/estj.v5i4.1015.

[56] Z. Mao, X. Li, X. Zhang, D. Li, J. Lu, J. Li, and F. Zheng, Optimization of Effluent Quality and Energy Consumption of Aeration Process in Wastewater Treatment Plants Using Artificial Intelligence. Journal of Water Process Engineering 63 (2024) 105384. https://doi.org/10.1016/j.jwpe.2024.105384.

[57] P. Patel, S. Gupta, and P. Mondal, Life Cycle Assessment (LCA) of Greywater Treatment Using ZnCl2 Impregnated Activated Carbon and Electrocoagulation Processes: A Comparative Study. Industrial & Engineering Chemistry Research 62 (2023) 3259–3270. https://doi.org/10.1021/acs.iecr.2c03353.

[58] S. Uludag-Demirer, N. Olson, R. Ives, J. P. Nshimyimana, C. A. Rusinek, J. B. Rose, W. Liao, Techno-Economic Analysis of Electrocoagulation on Water Reclamation and Bacterial/Viral Indicator Reductions of a High-Strength Organic Wastewater—Anaerobic Digestion Effluent. Sustainability, 12 (2020) 2697. https://doi.org/10.3390/su12072697.

[59] S. Uludag-Demirer, N. Olson, R. Ives, J.P. Nshimyimana, C.A. Rusinek, J.B. Rose, and W. Liao, Techno-Economic Analysis of Electrocoagulation on Water Reclamation and Bacterial/Viral Indicator Reductions of a High-Strength Organic Wastewater—Anaerobic Digestion Effluent. Sustainability 12 (2020) 2697. https://doi.org/10.3390/su12072697.

[60] F.Y. AlJaberi, S.M. Alardhi, S.A. Ahmed, A.D. Salman, T. Juzsakova, I. Cretescu, P.-C. Le, W.J. Chung, S.W. Chang, and D.D. Nguyen, Can Electrocoagulation Technology Be Integrated with Wastewater Treatment Systems to Improve Treatment Efficiency? Environmental Research 214 (2022) 113890. https://doi.org/10.1016/j.envres.2022.113890.

[61] A. Shahedi, A.K. Darban, F. Taghipour, and A. Jamshidi-Zanjani, A Review on Industrial Wastewater Treatment via Electrocoagulation Processes. Current Opinion in Electrochemistry 22 (2020) 154–169. https://doi.org/10.1016/j.coelec.2020.05.009.

[62] A. Tahreen, M.S. Jami, and F. Ali, Role of Electrocoagulation in Wastewater Treatment: A Developmental Review. Journal of Water Process Engineering 37 (2020) 101440. https://doi.org/10.1016/j.jwpe.2020.101440.

[63] A. Al-Yaqoobi M., and M. Al-Rikabey N., Electrochemical Harvesting of Chlorella Sp.: Electrolyte Concentration and Interelectrode Distance. Chemical Industry and Chemical Engineering Quarterly 29 (2023) 23–29. https://doi.org/10.2298/ciceq210815010a.