



Electrocoagulation in Wastewater Treatment: A Comprehensive Review on Parameters and Applications

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ABSTRACT

Electrocoagulation (EC) is a widely recognized and effective electrochemical treatment method used for removing various contaminants in liquid wastewater. It is capable of reducing a broad spectrum of pollutants, including heavy metals such as lead and cadmium, fluoride ions, dye molecules, oils, and pharmaceutical residues. The efficiency of EC depends on multiple parameters, including current density (which influences the rate of coagulation), pH level (affecting electrochemical reactions), electrode material (such as aluminum or iron), and the conductivity of the solution (which impacts energy consumption). Compared to conventional chemical coagulation processes, EC offers notable advantages by more effectively destabilizing fine colloidal particles, leading to faster aggregation and sedimentation, while consuming less energy. This review highlights recent technological advancements in EC applications, pointing out that most studies have been conducted at the batch scale, with relatively limited progress in developing continuous operation systems. The main challenges hindering large-scale implementation include electrode passivation (which reduces efficiency over time), sludge management issues, and the need for energy consumption optimization. To address these challenges, various strategies such as improving reactor design, developing hybrid treatment systems, and integrating EC with other processes are being explored. Overall, EC exhibits significant potential as a sustainable, flexible, and cost-effective technology for wastewater treatment. However, ongoing research is crucial to enhance the operational stability of continuous systems and ensure long-term sustainability, thereby facilitating broader industrial adoption of this promising technology.

INTRODUCTION

Water is a vital resource for industrial, agricultural, and domestic use. However, rapid industrialization and population growth have increased wastewater generation, which often exceeds the capacity of conventional treatment systems. In many cases, wastewater discharged into rivers, lakes, or other water bodies still fails to meet environmental quality standards, contributing significantly to global water pollution and ecosystem degradation [1][2]. Meanwhile, the wastewater generated by each industry is processed in Wastewater Treatment Plants (WWTP) using open pond systems that need a sizable tract of land and the use of chemical compounds [3]. The treated effluent is then discharged back into natural water bodies. According to Regulation No. 5 of 2014 of the Minister of Environment, effluents released into the environment must comply with wastewater quality standards. Nevertheless, in practice, many discharges still exceed permissible limits, causing severe environmental pollution, particularly in aquatic ecosystems.

Currently, water pollution has become widespread, resulting in the destruction of aquatic ecosystems. Water pollution is a condition caused by the input of pollutant loads/waste discharges in the form of gases, dissolved substances, and particulates.

Pollutants entering water bodies can come from the atmosphere, soil, runoff from agricultural land, domestic waste, urban areas, industries, and other [4]. Pollution occurs when substances in the environment cause undesirable changes, whether physical, chemical, or biological. According to Government Regulation No. 82 of 2001 [5], the introduction of living things into water is known as water pollution, pollutants, energy, and/or additional substances into water due to human activity additional substances into water due to human activity, resulting in a decline in water quality to a certain level that causes it to no longer function according to its intended use.

One major source of water pollution is liquid waste from industries such as palm oil processing and textiles. Palm oil production, one of the world's largest industries, generates substantial wastewater. Palm Oil Mill Effluent (POME) is produced at a rate of approximately 550–670 kg/ton of fresh fruit bunches [6]. The processing of palm oil generates solid waste and liquid waste known as Palm Oil Mill Effluent (POME). POME contains a high level of inorganic and organic materials, as indicated by its Total Suspended Solids, Chemical Oxygen Demand, Biochemical Oxygen Demand, low pH, and fats and oils [7]. According to the Minister of Environment, Regulation No. 5 of 2014 [8], the content of POME exceeds the threshold limit for waste quality standards. The environment will suffer negative

impacts if waste prevention and treatment are not carried out, such as water pollution that can poison aquatic biota, cause odors, and produce methane and carbon dioxide, which are contributors to the greenhouse effect.

When oil palm fruit bunches are processed into crude palm oil, POME is a byproduct [9][10][11]. POME originates from condensate from the sterilization, water used in the process of clarifying, hydrocyclone water (claybath), and wash water from the mill. Each ton of fresh fruit bunches produces 0.7 m³ of liquid waste [9][12][13][11]. POME generally has a high temperature ranging from 70-80 °C, is dark brown in color, contains suspended dissolved solids in the form of colloids and oil residues, and has a high BOD value of 25,000 mg/L, COD ranges from 35,000 to 56,000 mg/L, TSS between 40,500 and 50,500 mg/L, total nitrogen value of 750 mg/L, and oil and fat content of 2,500-3,075 mg/L [9][11].

Electrocoagulation (EC) has emerged as a promising alternative for treating such wastewater. Unlike conventional chemical coagulation, EC employs sacrificial metal electrodes that release cations into water, promoting the coagulation and removal of contaminants. Simultaneously, side reactions enhance the separation of flocculated particles. Numerous studies have examined the influence of operational parameters on EC performance, including initial contaminant concentration, current density, applied voltage, processing time, pH, temperature, electrode spacing, stirring speed, and supporting electrolytes [14][15][16][17][18][19]. Over the past decade, research has increasingly shifted from batch to continuous EC systems, with many researchers first optimizing batch processes before scaling up to continuous operations [20][21][22][23][24][25][26].

Designing an efficient EC reactor requires proper modeling, as it influences performance and scale-up feasibility [27]. To minimize energy consumption, research has focused on electrode configuration [28], process integration with sedimentation and sludge separation units [29][30][31], and current distribution analysis [32]. Critical operational factors such as residence time, flow rate, and electrode type significantly affect energy efficiency. Although no universal reactor design exists, continuous EC systems are consistently developed based on insights gained from batch-scale operations, with adjustments in geometry and electrode arrangement tailored to specific contaminants.

Recently, research has also explored hybrid approaches by integrating EC with other treatment technologies to enhance efficiency and broaden the applicability of EC for both organic and inorganic pollutants. Given its demonstrated effectiveness, EC is increasingly being studied for the treatment of POME. This development represents a step toward scaling EC for industrial applications, enabling wastewater reuse and minimizing environmental discharge. Ultimately, the integration of EC into palm oil wastewater treatment could provide an effective solution for mitigating water pollution while supporting sustainable industrial practices.

ELECTROCOAGULATION PROCESS

Theoretical Background

The fundamental idea behind electrocoagulation (EC) is "electrolysis," which is the breakdown of molecules using electricity. Michael Faraday first proposed the idea of electrolysis in 1820. Ions can move across electrodes due to this mechanism, which occurs in an electrolyte solution. Positive ions flow toward the cathode of an EC cell, where reduction happens, while negative ions flow toward the anode, where oxidation occurs [33][34]. This process involves combining wastewater with saltwater to electrolyze it. When the EC process was first being developed, the primary objective was to produce chlorine to reduce odors and disinfect wastewater. As a water treatment method, EC has a lengthy history. For ten years, wastewater treatment facilities employed this method, which was initially introduced in London in 1889 [35]. The EC method for purifying ship bilge water was discovered and patented by A. E. Dietrich in 1906.

In 1909, J.T. Harries patented an electrolysis technique using aluminum (Al) and iron (Fe) electrodes for wastewater treatment [36]. However, high electricity costs limited its early application. Electrolysis later gained attention for its superior ability to remove organic and inorganic contaminants compared to conventional coagulation. Large-scale electrocoagulation for drinking water treatment began in the U.S. in 1984 [37]. This method effectively removes bacteria, emulsified oils, suspended solids, and heavy metals by combining flotation, coagulation, and electrochemistry, although limited studies explore their integration [38]. Despite its efficiency, electrochemical treatment saw limited use in the 20th century until improvements reduced power consumption and sludge generation [39]. Recent advances allow operation with renewable energy sources at low currents [40]. With minimal chemical use, low-cost non-toxic electrodes, and reduced environmental impact, electrocoagulation is now considered an eco-friendly technology [41].

As shown in Figure 2, the EC unit consists of an electrolytic cell with a cathode and an anode that are submerged in an electrolyte solution and externally connected to a power source. An equal amount of electrons is released when the metal dissociates into divalent or trivalent metal ions, and the anode is oxidized when current passes through the electrolytic cell. Even though the electrodes are made of the same material, dissolution only occurs at the anode [34]. Equation (1) provides Faraday's law, which uses the current being applied density to calculate the quantity of metal ions generated [42].

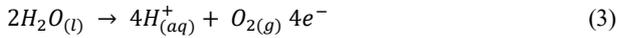
$$m = \frac{ITM_w}{ZF} \quad (1)$$

Where, m = mass of the dissolved anode, I = current, T = operating time, M_w = molecular weight of the material, F = Faraday's constant (96.485 C/mol), Z = number of electrons involved in the reaction.

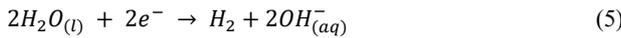
The EC process involves the electrochemical formation of compound species in solution by passing an electric current through electrodes. The resulting compound species disrupt the stability of colloidal particles through charge neutralization,

leading to the formation of larger flocs with trapped impurities. Flotation or sedimentation can be used to remove these flocs from the solution [43][44]. Metal ions are formed at the anode. Concurrently, the cathode produces hydrogen gas, which aids in the ascent of the agglomerated particles out of the water. Therefore, this process is sometimes referred to as

Anode :

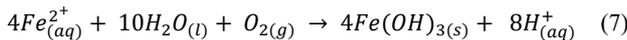


Cathode :



For the iron electrode, Fe(OH)_n, where n = 2 or 3, two processes for the manufacture of iron hydroxide have been presented [17]. 4Fe(OH)_{3(s)} is produced in the first mechanism (Equations (6)–(9)), whereas Fe(OH)_{2(s)} is produced in the second mechanism (Equations (10)–(13)).

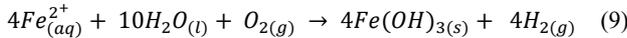
Anode :



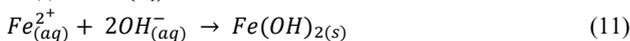
Cathode :



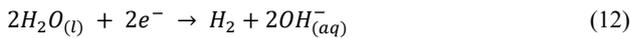
General Reaction :



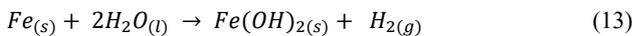
Anode :



Cathode :



General Reaction :

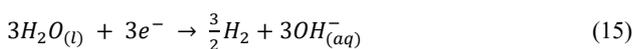


In addition, using an aluminum electrode, the following reaction is carried out [46]:

Anode :



Cathode :



After the formation of the Al_(aq)³⁺ ion and OH⁻, a reaction occurs that forms various types of monomeric and polymeric compounds with different charges [47], which eventually changes into something insoluble, Al(OH)₃ hydroxide, forming flocs with a large surface area where absorption takes place [46]. These flocs form in the mixture based on the pH and the concentration of the precipitating metal. The increase in Al³⁺ and OH⁻ concentrations

electrocoagulation. Aluminum and iron electrodes are effective in removing contaminants under optimal operating conditions [17]. The reaction mechanisms that occur can change because they are dynamic processes that evolve during the course of the process or in response to changes in operational parameters. This process also varies depending on the type of contaminant. Nonetheless, it can be used for the following anode and cathode reactions [45]: drives the equilibrium and the formation of insoluble amorphous species that remove contaminants through coprecipitation [47]. During the process, a number of reactions take place, forming the species Al(OH)₃ (Equations (16)–(18)) [48] Al(OH)₄⁻ and other insoluble species begin to appear when the pH increases during the process (Equation (19)).

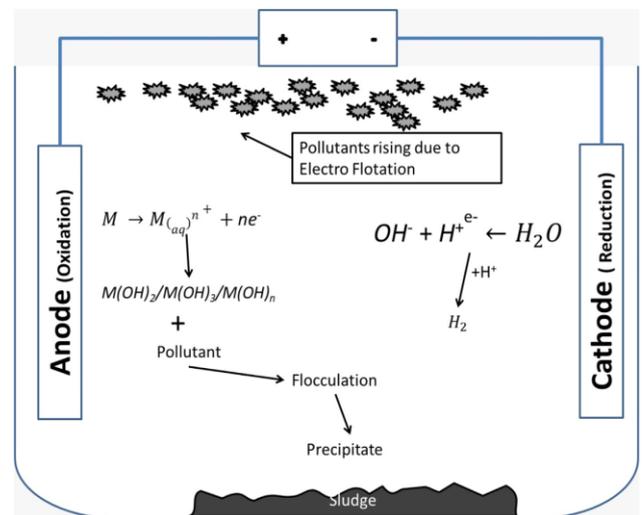
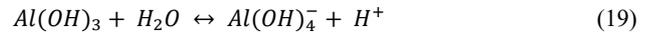
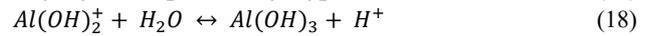
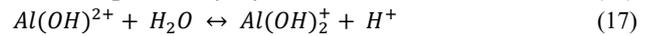
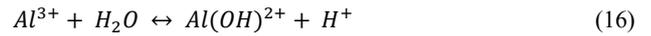


Figure 2. Schematic representation of the electrocoagulation cell.

Operation Parameters

Recent advancements in electrocoagulation (EC) show that contaminant removal efficiency depends on operational parameters such as initial pollutant concentration, current density, pH, electrode material, number and arrangement of electrodes, conductivity, and process time [15][16][18][45]. Figure 3 illustrates how the primary parameters affect the efficiency of the EC process. These factors have been extensively discussed and evaluated for various pollutants, and further references can be found elsewhere [27][43][45][38][34]. The efficiency of the EC process mainly depends on the type of solid species formed and the effectiveness of mass transfer and mixing. Key operational parameters include pH, current density, electrolyte type, electrode material and arrangement, conductivity, and process time. Additional factors such as gas bubble formation, resistances (Faradaic and Ohmic), electrode passivation, and reactor hydrodynamics also play significant roles. Overall, optimal reactor design and operating conditions are crucial for maximizing contaminant removal efficiency.

Distance Between Electrodes

The distance that exists between the electrode and its surface is one of the primary variables that directly impacts electrocoagulation performance. The movement of different existing ions during the EC process concentrates the solution close to the cathode. Stirring the primary solution reduces this impact [33]. The EC technique increases electrical resistance by partially filling the gap between the electrodes with gas. Through the perforated and wavy electrodes, the generated gas is released [49]. When calculating the ideal operating cost of a nuclear reactor, the distance between the electrodes is a crucial factor. High-conductivity waste is processed using a wider electrode gap (at a constant current density) when extensive testing is conducted to determine the reactor's ideal operating performance. Likewise, reducing the distance between electrodes can save energy for low-conductivity waste [46].

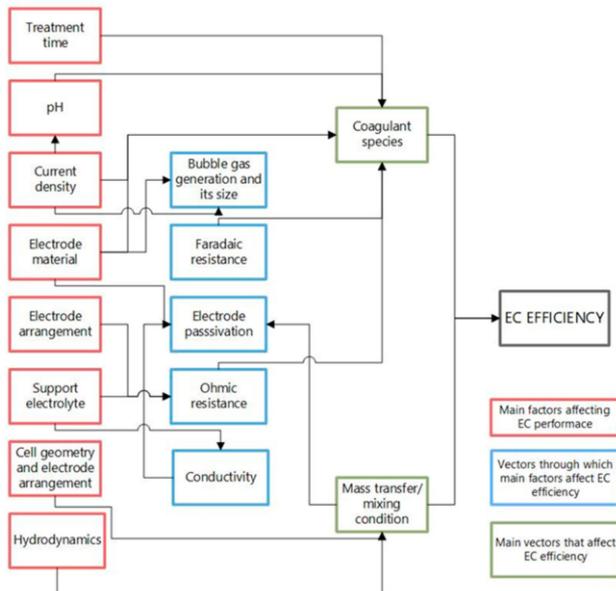


Figure 3. The main factors influencing the EC process [43].

Electrode spacing is a key parameter in electrocoagulation, as it directly influences the electric field between the anode and cathode. At very small distances, pollutant removal efficiency decreases due to the dispersion of metal hydroxides caused by strong electrostatic interactions. As the spacing increases toward an optimal value, removal efficiency improves because metal hydroxides have sufficient time to aggregate and precipitate contaminants. However, when the distance becomes too large, ion migration slows, and the electrostatic effect weakens, reducing overall process efficiency [15].

During wastewater treatment, electrode distance affects removal efficiency. Using Al electrodes, the best phosphate removal occurs at pH 3, a 5 mm gap, and 3.2 mS/cm conductivity [40]. There should be at least 10 mm of space between electrodes when using low voltage. Otherwise, ECR polarity reversal needs to be performed on a regular basis, as floc deposits are a common occurrence. For instance, during the EC process, the electrode spacing is kept between 10 and 30 mm in order to eliminate the ciprofloxacin medication contamination from wastewater [34]. A recent study of statistics [50][51][52] also found that the distance between electrodes is a significant factor in removing acidic and basic dyes from the solution.

The electrode material's effects

The performance of electrocoagulation (EC) reactors is strongly dependent on the type of electrode materials used. Various metals, such as Al, Fe, Ag, Mg, Ca, and Zn, have been tested; however, Al and Fe are most commonly used. Electrodes can be made from plates or metal wastes like shavings and scraps [50][53]. In certain applications, such as oil removal, aluminum electrodes have been found to be more effective than iron electrodes. This may be due to the better absorption capacity of aluminum oxide. Several specific metal ions are required to remove certain contaminants. The most widely utilized electrodes for wastewater treatment are iron and aluminum because of their easy availability, affordability, and high solubility. Iron is chosen because it is inexpensive. Aluminum plates are used alone or in conjunction with iron plates for wastewater treatment because of their excellent flocculation efficiency. Large concentrations of the water's Ca^{2+} or Mg^{2+} ions suggest the use of stainless steel cathode material [54].

New developments have enabled the use of hybrid electrodes consisting of different combinations, such as the Fe-Al electrode, which provides better results over a wide pH range [55]. To remove arsenic from wastewater, various geometries, including filter plates, rods, and balls, are employed, achieving efficiencies of around 75-100% under different operating conditions. Compared to Fe electrodes, Al is effective in reducing COD. However, when grease and oil were removed using Aluminium and stainless steel electrodes, no discernible results were obtained [34]. Inert cathode materials like titanium or graphite, having a covering of metal oxide, are advised if a sizable concentration of magnesium/calcium ions is anticipated in the treated effluent [56]. It is crucial to ensure that no impurities remain among the residues. The surface of the electrode plate needs to be cleaned on a regular basis because the buildup of sludge on the electrode restricts the release of metal cations into the liquid [33].

Initial pH Effect

Based on the results of the experimental investigation, pH has a big effect on the EC. Throughout the electrocoagulation process, the solution's pH fluctuates. It is evident that not every impurity gets eliminated from the solution at the same pH. Conversely, the efficacy of pollutant removal is significantly impacted by the wastewater's final pH value [57]. The efficacy of Cr^{6+} removal is significantly influenced by the pH of the solution, according to research on the removal of hexavalent chromium from synthetic solutions applying EC. They experimented with synthetic solutions at various pH levels and discovered that the most effective way to remove chromium was at pH 4 [58]. The efficacy of the EC system reached 90% when wastewater from the textile industry was examined utilizing Fe electrodes with starting pH values ranging from 3 to 9; however, there was no association with the removal of pollutants. noted using a starting pH [56]. Al electrodes served to remove phosphorus from laundry wastewater. The findings indicate that if the initial pH value is below 6 and above 8, the clearance rate is low [59]. Additionally, it has been noted that the efficacy of pollutant removal is impacted by a distinct interplay of pH and current density.

Electrocoagulation Time

Electrocoagulation time influences contaminant removal efficiency. Longer durations increase pollutant removal by generating more metal hydroxides and flocs, but once the optimal time is reached, additional treatment does not improve efficiency, as sufficient flocs are already available [60]. The optimal electrocoagulation times are 3 and 2 hours for smooth surface electrodes and elongated electrodes, respectively [61][62].

Resources, electrode type, power consumption, virus and bacteriophage clearance, and other factors all affect total operating time, which is a mutually dependent metric. We talk about how well DC, AC, and APC remove pollutants. APC is regarded as the best since it has lower running expenses, a shorter operating duration, and less electrode corrosion, even though the efficiency is the same in all three scenarios. Different electrode configurations (Al-Al, Fe-Fe, and Fe-Al), varying durations (15, 30, and 60 minutes), and diverse current densities (0.04–0.08 A) were employed in the investigation. In a coagulant role [38][63]. Because it used less current (0.04 amp) for the same 15-minute working time, the Fe-Al combination was selected from the three-electrode arrangement. The quantity of dissolved electrode material from each electrode plate was 0.02 g for Fe and 0.17 g for Al, as determined by weighing the electrodes before and after EC [64]. In short, the total residence time of an operation is determined by the contaminants to be removed and the desired efficiency, which heavily depends on the process cost.

Density of Current (CD)

The quantity of metal ions discharged by the electrode is determined by the CD, which is defined as current per unit area. Because it influences the pace of bubble formation, how quickly coagulant is added, and the size and growth of flocs, CD is a crucial EC parameter that impacts EC efficiency [34][65]. The anode dissolution rate increases with the increasing CD. This increases the amount of metal hydroxide flocs and enhances the efficiency of pollutant removal. Because there are enough metal hydroxide flocs available for pollutant precipitation, increasing the current density over the ideal current density has no influence on the efficacy of pollutant removal [66].

The CD, which is also affected by other limitations, including water flow rate, pH, and temperature, is directly proportional to the dissociation of metal ions into the solution. Data gathered for the study by a few researchers [67][68] revealed that factors including operating time, applied CD, water pH, and Fe content affect the EC unit's performance. Studies show that Fe removal in electrocoagulation generally increases with reaction time and current density, but decreases when IC rises. However, neither strongly acidic nor basic conditions provide optimal removal. The findings also indicate that pollutant elimination is not directly proportional to current density, as no significant improvement occurs above 10 mA/cm². For instance, at 6 minutes, increasing current density from 5 to 10 mA/cm² enhances removal efficiency from 67% to 96%. Yet, further increase to 20 mA/cm² destabilizes the coagulation process due to excessive heating of the solution, thereby reducing overall efficiency [69]. Since higher currents translate into higher economic expenses, an appropriate current value must be selected [70][71][72].

Temperature

The starting point of the wastewater is another factor that affects the EC process and is unrelated to other factors. Considering that microbes are known to be sensitive to temperature, this is one of the most important characteristics. According to Sediqi et al. (2021) [73][74][75][76] a rise in temperature increases molecular mobility, which causes more particle collisions and improves floc formation and pollution clearance. During EC, the system temperature rises as current is applied. A higher initial temperature can enhance COD removal, but excessive heating causes floc dispersion and reduces efficiency. This effect is linked to increased current density and solution instability, which ultimately limit the overall removal performance. This could be because the coagulation process is more volatile and the solution temperature is rising. We recognize that as the temperature rises, water's conductivity also increases, enhancing the process's removal efficiency, as shown by Ref. [52][53][54][57]. Nonetheless, the EC system often uses monitoring external parameters to control the solution temperature [77]. By simplifying the EC process, the higher suspension temperature has significantly enhanced the lime-clay suspension's ability to remove turbidity while consuming less current. The chemical characteristics of Al are the cause of the improved removal mechanism's efficacy, because the temperature of the suspension increases the concentration of coagulated Al species (Al(OH)²⁺) [78].

Electrode Arrangement

Electrode configuration is another key factor affecting EC efficiency. Systems can operate in monopolar or bipolar modes. In monopolar parallel (MP-P), anodes and cathodes are directly connected to the power supply, with the current distributed according to the cell resistance. In monopolar series (MP-S), internal electrode pairs are connected in series, producing higher potential differences, while inner electrodes act as sacrificial components. In bipolar parallel (BPP), only the outer electrodes are connected to the power supply, while the inner electrodes remain unconnected, allowing for alternative current paths and influencing overall efficiency. The inner electrode's neighboring side gets polarized and carries a charge opposite to the other electrode when current passes through it [38][33][34][79].

Numerous studies have evaluated the effectiveness of pollution removal in terms of operational costs. It was also investigated how well four Al electrodes coupled in three distinct configurations—MP-P, MP-S, and BP-P—performed [80]. Thus, the MP-P connection form can be considered effective. An analysis of the costs of the MP-P, MP-S, and BP-P connections for reducing arsenic from drinking water as a function of CD, pH, and working time revealed that MP-P is the most economical option for Fe and Al electrodes [15]. The discovery indicates that although the design that is monopolar design has lower running costs, the bipolar arrangement is more effective at eliminating pollutants [56].

Literature indicates that EC efficiency is influenced by multiple factors, but their effects vary with the type of wastewater. For example, in treating emerging contaminants such as TNP, the removal efficiency remained stable across a wide pH range (5–11), with rates of 80.7%, 82.3%, 85.0%, and 84.2% at pH levels

of 5, 7, 9, and 11, respectively. The study also demonstrated that a higher current density significantly enhanced removal performance [81]. Processing textile waste, however, did not reveal a comparable trend. It was found that the removal of COD was more effective at a current density of 14 mA/cm², as opposed to 20 mA/cm² [82]. Overall, it appears that the primary operating parameters discussed above must be adjusted to achieve the optimal contaminant removal efficiency for each distinct type of wastewater, based on the experimental findings obtained from a variety of wastewater types.

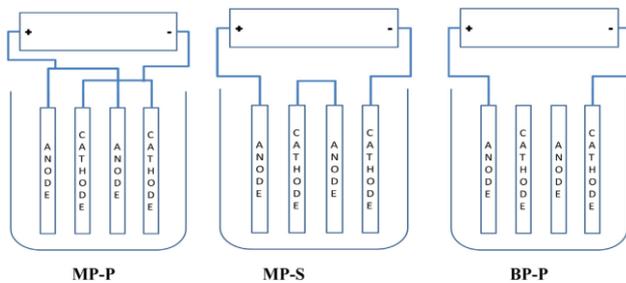


Figure 4: Various designs of electrode arrangements

APPLICATION OF ELECTROCOAGULATION

EC systems are designed to be simple, cost-effective, and applicable to a wide range of wastewater types. Recent studies have also highlighted novel applications, such as enhancing the production of marine microalgae through induced dielectrophoresis (iDEP). Using an AC power source with asymmetric Al electrodes, the system achieved up to 90.9% efficiency at 7.1 mA/cm² within 10 minutes, with an energy consumption threshold of 4.62 kWh/kg [77]. Although the two methods yielded the same harvesting efficiency, when the previous figure is utilized as the ideal operating state, compared to the Alternating Current module, the Alternating Current Dielectrophoretic (ACD) module produces biomass with a 52% lower Al content. [83].

Because it generates up to ten liters of waste for every liter of produced milk, the dairy processing business is regarded as the most water-intensive industry globally [73]. Dairy effluent is characterized by high BOD and COD due to its rich organic content, including fats, oils, proteins (such as whey and casein), nutrients, and cleaning agents. It often appears white (or yellowish-green for whey) and produces strong odors. The rapid decomposition of milk wastewater depletes dissolved oxygen, creating anaerobic conditions that release harmful gases and unpleasant smells. When discharged untreated into rivers or land, this waste poses significant environmental risks [74]. To ascertain the benefits and drawbacks of traditional EC and indirect EC in eliminating contaminants from milk waste, a study has been carried out [75][76]. The authors concluded that calcium chloride was an excellent electrolyte. At the same time, turbidity and phosphate removal rates increased to 95% at a pH of 7, leaving organic materials in the solution. Because the residual organic elements increased the amount of pollutants in the solution, making it non-recyclable, the solution stayed stable for forty-five hours after electrocoagulation. Economically speaking, indirect EC is considered less expensive than the standard EC method, but it is more successful.

Untreated tannery effluent poses severe environmental risks due to its high organic load and elevated levels of nitrogen, ammonia, sulfates, sulfides, salts, and other minerals. It is typically brown, odorous, and contains high TDS, BOD, and COD. These contaminants contribute to eutrophication, oxygen depletion, biodiversity loss, and increased salinity in aquatic systems. Studies report COD levels exceeding 2000 mg/L, far above the permissible 1000 mg/L for discharge, underscoring the necessity of treating tannery wastewater before disposal [84]. Researchers systematically treat the waste using EC, photolysis, ultraviolet, or a combination of the two [75]. Compared to the efficiency of EC and UV alone, which are 85.7% and 55.9%, respectively, the sequential waste treatment employing UV and EC combination has demonstrated efficacy, resulting in a COD reduction of 94.1% [69][85].

In this case, the EC setup consists of iron electrodes and a microbubble generator to produce bubbles [85][86][87]. Some researchers want to investigate the effects of adding microbubble water in conventional EC cells. To minimize pollution from textile dyes, the researchers conducted several tests and recommended optimal values for each parameter. In an effort to create a continuous flow EC reactor for the elimination of azo dyes, they decided to focus their work on methyl orange [88]. The cathode and anode for the continuous reaction were folded Fe plates, according to the authors. Along with identifying the ideal circumstances, it was noted [89] under comparable circumstances, the decolorization rate was 92.35% higher than that of the flat electrode system. (pH, waktu, arus kerapatan, etc.). The researchers also investigated how fluid flow, plate inclination, and plate distance impacted system efficiency and found that each of these factors had a significant effect.

Researchers are working to remove fluoride using EC and evaluate its effectiveness in doing so because fluoride levels in home water that are higher than allowed might lead to major health problems [90]. The authors made a similar synthetic solution after gathering samples from several Tanzanian rivers. EC is a practical method for eliminating fluoride in large doses, as indicated by the positive outcomes of the experiments. According to reports, the TBS and WHO suggest that drinking water has a fluoride concentration of 1.5 mg/L, which can be reached with a 90% rate of removal [91]. It has been determined that the ideal voltage range for the EC approach to effectively remove fluoride from water is between 30 and 35 V [92].

Numerous functions applicable to various applications are provided by microalgae. Microalgae-derived biofuel is thought to be a promising substitute fuel [93]. To harvest *Nannochloropsis salina*, an EC system coupled to a fuel cell made of metal and air is to be constructed [94][70]. Iron, Aluminium, and Magnesium were the three types of electrodes they used in their experiments. Their primary goals were to assess the efficiency of metal-air fuel cells, learn methods for collecting marine microalgae, and examine the differences between the power generated by the EC process utilizing fuel cells and that produced through the EC procedure with standard resources [71].

Palm oil mill effluent (POME), similar in composition to olive mill wastewater, contains hazardous contaminants and poses serious health and environmental risks if discharged untreated.

Table 1. Electrocoagulation applications in the treatment of wastewater.

Type Of Waste	Electrode (Anode/Cathode)	Experimental Conditions	Removal Efficiency (%)	Reference
Synthetic wastewater and actual wastewater	Al-Al Fe-Fe	The size of the EC reactor is 15 × 20 × 22 cm. Using 2 types of electrodes, namely Fe (P:10 cm, L:10 cm, and T:0.01 cm) and Al (P:3 cm, L:1.9 cm, and T:1.2 cm). The current used ranges from 5 mA/cm ² to 11 mA/cm ² . Electrocoagulation time (5–20 minutes).	The turbidity removal efficiencies reached a maximum value of 99%.	[98]
Distillery industrial wastewater (DIW)	Al-Al Fe-Fe	Capacity of the UV/DC/AC/Elc reactor (2 L, made from acrylic sheets). It uses 2 types of electrodes, namely iron and Aluminium, with an electrode surface area of 70 cm ² . The electric current used is 0.1 – 0.9 A. The processing is supplemented with low-pressure UV lamps, with a power range of 8 to 40 Watts.	COD-100 % and color -100 %	[99]
Synthetic wastewater dan Laundry wastewater	Fe-Stainless Steel	Using electrodes iron anode and a stainless steel cathode. The reaction is set at 23 °C, 15 V, and a current of 1 A.	removed numerous pollutants 70%–93.5%.	[100]
Red dye 40 dissolved in water	Fe-Fe	The sample used is red dye 40 dissolved in water with concentrations of 1, 2, 5, 10, 20, 40, 80, and 160 ppm. The experimental design used has two variables: voltage values (10 V, 15 V, 20 V) and electrocoagulation duration. (3 menit, 6 menit, 10 menit, 20 menit, 40 menit, 60 menit).	Color removal 93,85%	[101]
Organic waste containing methylene blue	Al-Al	CD (100, 150, 200, 250 A/m ²), pH (3, 4, 5, 7, 9, 11), electrolysis time (30, 60, 120 minutes), sodium chloride concentration (0.5, 1, 2 g/L), and initial dye concentration (10, 20, 45, 60 mg/L)	Color removal 97,81%	[102]
Dairy industry	Al-Al	pH 5.00, Time 25.00 min, Current density 6.16 mA/cm ²	COD 57%	[74]
Textile water	Fe-Fe	Time 20 minutes, distance of electrodes 4 cm, pH 8.50, and current density 14–17 mA/cm ²	COD 76%, Color 95%	[82]

Research has focused on optimizing EC parameters—such as current density, electrolysis time, pH, and electrode spacing—to improve floc formation and pollutant removal efficiency [72]. The researchers used a light microscope to assess the size and composition of the flocs.

Furthermore, EC can treat a variety of textile wastes with a respectable removal efficiency. High color levels caused by unused dyes, excessive salt, COD, high temperatures, and a broad pH range are typically linked to textile waste. Additionally, this waste may contain substances that are harmful, toxic, or mutagenic to various animals or microbial species. When processing textile waste, researchers have reported removal efficiencies of 76% for COD and 95% for color [82]. Hospital and pharmaceutical wastewater contain resistant pollutants—such as pharmaceuticals, heavy metals, suspended solids, and high COD—that are not effectively treated by conventional biological methods. EC has shown promise in addressing these contaminants. For example, studies report up to 88.75% [95] ciprofloxacin removal using aluminum electrodes with NaCl electrolyte at 12.5 mA/cm² and 1.0 cm spacing. Similarly, Ayurvedic wastewater treatment achieved 58.3% removal efficiency with electrode separations of 10–15 mm, highlighting the potential of EC for biologically resistant effluents [96].

Moreover, wastewater containing emerging pollutants (EP) can be effectively treated by electrocoagulation. Recently, TiO₂-based nanoparticles (TNP) have become increasingly popular for

various applications in the technology, culinary, and medical sectors. Waste that contains these nanoparticles, however, may be harmful to people's health. TNP damages cells by penetrating red blood cells and degrading DNA proteins. To extract TNP from wastewater, researchers have worked on developing an effective EC reactor [97]. In EC treatment of TNP-contaminated wastewater, using HCl as the electrolyte with two Fe electrodes spaced 2 cm apart achieved over 95% removal at neutral pH and 100 mA.

Another emerging concern is microplastics, which originate from industrial and consumer waste. Their small size and low density make them easily ingested by aquatic organisms, causing physical harm and enabling toxic compounds to enter the food chain, posing risks to both ecosystems and human health. Recent studies have also explored EC as a promising method for microplastic remediation in wastewater [81]. EC has been widely utilized in various sectors due to its effectiveness in removing a range of organic and inorganic contaminants. Wastewater from the petroleum, paint, pulp, automotive, and municipal sectors is among the many industrial pollutants that EC is frequently used to treat. Table 1 provides information on the experimental setup required to achieve the highest removal efficiency for different wastewater types

OPPORTUNITIES AND CHALLENGES

Although EC has been around for a while, reactor design and operation have not yet been approached systematically. At the laboratory level, EC has been effectively used to treat water pollutants. On the other hand, the scale is challenging to meet industrial standards [38] and specifically depends on lowering operating costs, characterization, and sludge disposal during operation. Because most of the present research focuses on eliminating specific pollutants rather than developing ideal reactor designs and operating conditions, the large-scale industrial implementation of EC has been postponed [103]. By creating such a model, EC technology will be able to leverage its design features and move beyond its current state of impracticability. Research on how to combine these technologies to create efficient EC technology for industrial applications is still lacking, despite the fact that EC is an integration of three distinct technologies [34]. Electrode passivation is the primary obstacle in EC applications. This is because it has been noted that after repeated use, the homogeneous and flat electrode's morphology transforms to a heterogeneous one. The passive layer that develops on the electrode's surface lowers the effectiveness of pollution removal while increasing power consumption. The high power consumption in wastewater treatment, which has a direct impact on operational expenses, is another significant issue that this system may encounter. Researchers must therefore concentrate on mathematical simulations and kinetic studies [104]. Thus, the success of this technology is determined by its ability to meet business objectives, such as reducing administrative and operational expenses. Technologies like adsorption, membrane technology, and biotechnology must contend with EC technology.

The flocs' properties, including compaction, growth rate, strength, size, weight, and potential for regeneration, pose the biggest obstacle to the effectiveness of EC and significantly affect its ability to treat wastewater [72]. Recent studies have shown that adding ferrate and sludge adsorbent (SA) enhances the removal of secondary organic matter from reclaimed wastewater, addressing the limited performance of basic coagulation for microorganic contaminants. Floc formation typically progresses through early aggregation, main growth, and size expansion into open structures, with denser flocs settling more easily. Larger flocs form with higher current and longer electrolysis times; however, excessive growth may lead to breakage before restabilization through continuous coagulant release. Electrode spacing also influences floc size, with smaller gaps reducing ohmic losses and promoting larger floc formation

The secondary effects of the additional reagents present another difficulty when treating wastewater via electrocoagulation. To improve EC efficiency, for instance, reagents with iron and aluminum salts are frequently used. Nevertheless, this causes the reclaimed water's chloride content to rise. Chlorides must also be eliminated due to the negative consequences of chloride residues, which can be achieved through non-selective treatment technologies. Because of the inherent challenges in eliminating chloride ions, selective or preferential methods are rarely employed.

CONCLUSION

Electrocoagulation (EC) is increasingly recognized as an eco-friendly and versatile technology for wastewater treatment. It can simultaneously remove organic, inorganic, and emerging pollutants, making it highly relevant for complex industrial effluents. Compared to conventional coagulation, EC reduces chemical use and sludge generation while achieving high removal efficiencies under optimized conditions. These advantages position EC as a promising alternative and an important tool for sustainable wastewater management

While EC offers significant advantages, its large-scale application is limited by electrode passivation, sludge management, and high energy demand, with most studies conducted at the laboratory scale. Future research should focus on reactor optimization, energy-efficient operation, integration with complementary treatments, and computational modeling to enhance understanding of system behavior. Coupling EC with renewable energy could enhance sustainability. Overall, advancing EC from lab to industrial scale will strengthen its role as a strategic wastewater treatment technology and support global sustainable water management efforts

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