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*Review*

# Electrocoagulation in Wastewater Treatment

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**Abstract:** A review of the literature published in from 2008 to 2010 on topics related to electrochemical treatment within wastewater was presented. The review included several sections such as optimization, modeling, various wastewater treatment techniques, analytical and instrumentation, and comparison with other treatment methods.

**Keywords:** wastewater treatment; electrochemical treatment; electrocoagulation; coagulation; sacrificial anodes

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## 1. Definition of Electrocoagulation-Flotation (ECF)

Electrocoagulation-electroflotation (ECF) technology is a treatment process of applying electrical current to treat and flocculate contaminants without having to add coagulations. Shammas *et al.* stated that coagulation occurs with the current being applied, capable of removing small particles since direct current applied, setting them into motion. Also electrocoagulation could reduce residue for waste production [1].

Electrocoagulation consists of pairs of metal sheets called electrodes, that are arranged in pairs of two—anodes and cathodes. Using the principles of electrochemistry, the cathode is oxidized (loses electrons), while the water is reduced (gains electrons), thereby making the wastewater better treated. When the cathode electrode makes contact with the wastewater, the metal is emitted into the apparatus.

When this happens, the particulates are neutralized by the formation of hydroxide complexes for the purpose of forming agglomerates. These agglomerates begin to form at the bottom of the tank and can be siphen out through filtration. However, when one considers an electrocoagulation-flotation apparatus, the particulates would instead float to the top of the tank by means of formed hydrogen bubbles that are created from the anode. The floated particulates can be skimmed from the top of the tank.

To consider how effective the ECF reactor can be, one must consider the following inputs or variables—wastewater type, pH, current density, type of metal electrodes (aluminum, steel, iron), number of electrodes, size of electrodes, and configuration of metals. These variables would affect the overall treatment time, kinetics, and also the removal efficiency measured.

Electrocoagulation-flotation is an alternative method to classic chemical coagulation for many reasons. ECF is capable of reducing the need for chemicals due to the fact that the electrodes provide the coagulant. However, many individuals still use chemical coagulants to attempt to enhance treatment. Traditionally, chemical coagulation involves the use of alum (aluminum sulfate), ferric chloride ($FeCl_3$), or ferrous sulfate ($Fe_2SO_4$) which can be very expensive depending on the volume of water treated. When applying the coagulant, the coagulant performs a similar function as the electrodes, neutralizing the charge of the particulates, thereby allow them to agglomerate and settle at the bottom of the tank. In addition, electrocoagulation-flotation is capable of reducing waste production from wastewater treatment and also reduces the time necessary for treatment.

## 2. Optimization

By considering the Box-Behnken design of surface response analysis for color removal within distillery spent wash, Krisna Prasad *et al.* found that 95% color removal was obtained with 31 mA/cm$^2$, dilution of 17.5%, and 4 hour electrolysis design. At optimum conditions, the treatment efficiency was at 93.5% [2]. Chavalparit and Ongwandee concluded that removal of 55.43% COD, 98.4% oil and grease, and 96.59% suspended solids was obtained using a pH of 6.06, applied voltage of 18.2 V, and reaction time of 23.5 minutes when using the Box-Behnken design for biodiesel wastewater [3]. Kaparal *et al.* was able to determine the dye removal by the Taguchi method, by using an initial dye concentration of 100 mg/L, pH of 3, current density of 0.5 mA/cm$^2$, $CaCl_2$ concentration of 2.5 mM for the treatment of Bompalex Red CR-L dye. Experimental design involved an orthogonal array using 5 simultaneous parameters [4]. Tchamango *et al.* used electrocoagulation for artificial wastewater with milk powder to simulate dairy effluents, COD was reduced by 61%, phosphours by 89%, nitrogen 81%, and 100% turbidity. In addition with low conductivity and neutral pH, treated water would be possible reused, as reagent required was lowered for the aluminum anode for treatment [5]. Körbahti and Tanyolaç concluded that 100% pollution load, 61.6% COD, 99.6% color removal, and 66.4% turbidity were accomplished by an electrochemical reactor, where optimum conditions for conducting the experiment were at temperature of 30 degrees Celsius, 25 g/L electrolyte concentration, 8 V electrical potential, with a 35.5 mA/cm$^2$ current density. This was accomplished to treat simulated textile dye wastewater with NaCl electrolyte based on response surface methodology [6].

Hammami *et al.* concluded that electrochemical oxidation of chromium(III) from chromium(VI) was accomplished with titanium-platinum anodes for the purpose of treating tanning bath effluent. The

Doehlert design optimized Cl ions, temperature in degrees Celsius, pH, intensity of current, time of electrolysis. From the results, the authors observed that current intensity, COD (chemical oxygen demand), TOC (total organic carbon), and electrochemical oxidation were major parameters [7]. Olmez studied hexavalent chromium removal with stainless steel electrodes with electrocoagulation by response surface methodology and concluded that complete treatment could be accomplished by the elctrocoagulator with 7.4 A current and 33.6 mM electrolyte concentration (NaCl), a 70 minute application time and $FeSO_4 \times 7H_2O$ as a coagulant. The authors considered the use of a Central Composite Design for the optimization [8]. Arslen-Alton *et al.* concluded that the central composite design was used to optimize CI Acid Blue 193 treatment by electrocoagulation. The central composite design is capable of achieving maximum color, COD, TOC, by manipulating the COD, pH, electrical current density, and treatment time by means of a response surface quadratic model [9]. Cora and Hung were able to remove metallic ions between 90 and 99% after 30 minutes of treatment using an electrocoagulation/electrofiltration with a pH of 9.5 and cadmium chloride for the metallic ions [10]. Aleboyeh *et al.* concluded that Acid Red 14 had a 91% removal rate when current density reach 102 $A/m^2$, electrolysis time of 4.47 minutes, and a pH of 7.27. This treatment was obtained within an electrocoagulation batch reaction under a $2^3$ full factorial central composite face center design, where a second-order regression model was used [11].

Zodi *et al.* derived a statistic analysis using a Box-Behkey design for surface response analysis using electrochemical sedimentation. Having considered current density, pH, and electrolysis design, the authors were capable of studying the effects of COD, turbidity, TS removal, and sludge settling with aluminum electrodes [12]. Vasudevan *et al.* considered using mild steel as anode and cathode, removing 98.6% arsenate at a current density of 0.2 $A/dm^2$, and a pH of 7. Kinetics determined that the removal was within 15 minutes, following a second order rate absorption. Finally, Langmuir adsorption isotherm describes appropriately this condition [13].

## 3. Modeling

### *3.1. Kinetics*

Balasubramanian *et al.* modeled adsorption isotherm kinetics for arsenic removal from aqueous solutions by means of electrocoagulation through response surface methodology [14]. Thakur *et al.* concluded that COD and color removal of 61.6% and 98.4%, respectively, were capable of treating bio-digester effluent within an electrocoagulator. This was a result of a bio-digester plant followed by two-stage aerobic treatment. When considering a second-order regression model for this phenomena—pH, current density, inter-electrode distance, and electrolysis time as parameters, the model concluded an $r^2$ value of 0.9144 for COD and 0.7650 for color [15]. By producing a mathematical model, Canizares *et al.* determined that electrocoagulation can treat kaolin suspension by determining the total aluminum concentration and pH, along with reactivity and pollutant concentration. The authors noted the neutralization of kaolin particles and enmeshing particles with precipitation. The results of the model could produce an $r^2$ value of 0.92 [16]. Canizares *et al.* determined that a model comprised with Ericohrome Black T and oil/water emulsion where the primary mechanism operated were aluminum hydroxide precipitate and charge neutralization of

Eriochrome Black T, while one drop of aluminum precipitate was applied for oil/water emulsion removal. When applying this model, 96% of Erichrome Black T was removed, while 92% oil/water was emulsified [17].

Zaroual *et al.* concluded that 91% removal efficiency was capable for treating chromium (III) with aluminum anodes for electrocoagulation. Additionally, a mathematical model was established using central composite design, using a pH of 4.23, electrical potential of 9.14 V, 10 minute reaction time, and 27.5 ℃ temperature. Treatment efficiency of 91% could be completed with an energy consumption of 3.536 kWh/$m^3$ [18]. Arslan-Alaton *et al.* was able to model treatment of Acid Blue 193 by Central Composite Design. According to the model, COD, TOC, and color removal were chosen. Removal efficiency of 96% color, 82% COD, and 51% TOC was established for $Fe^{2+}$ concentration is 3 mM, $H_2O_2$ concentration is 25 mM, a reaction time of 10 minutes, pH of 3, and a COD of 245 mg/L were obtained for Fenton treatment, compared to 50 A/$m^2$, with a reaction time of 15 minute, pH of 7, and initial COD of 245 mg/L [19]. Saravanan *et al.* concluded that by using Acid Blue 113 with electrocoagulation was capable of removing 91% COD under 3 A/$dm^2$ of current density, pH of 6.5, and 2 g/L electrolytes concentration. The authors determined that this relationship resembled a pseudo-first order kinetic model [20].

Gadd *et al.* concluded that treatment efficiency was related to the electrode area, along with coagulant and bubbles, functions of electrode area, current density, and efficiency. This operation was completed using a vertical plate electrocoagulation treating molasses process wastewater [21]. Rodrigo *et al.* developed model for wastewater pollution considering hydrodynamic conditions using chemical reaction of reagents and pollutants, where a multivariable modeling of anodes was described. The model combined a macroscopic/maximum gradient approach for all processes with pseudo equilibrium [22].

### *3.2. Computer Modeling and Statistics*

Aber *et al.* concluded that an artificial neural network was capable of producing an $r^2$ value of 0.976 as compared to experimental data for treating synthetic and real electrocoagulation. Parameters included 30 minutes electrolysis time, pH between 5 to 8, the use of NaCl for better Cr(VI) removal (17.1 mg/L), and the use of iron electrodes as compared to Al (95% *vs.* 15% efficiency) [23]. Bhatti *et al.* determined that performance for treatment of Cr (VI) from 100 mg/L using Al-Al electrodes, would notice a 100 $cm^2$ surface area, and 15 mm electrode distance. Electrocoagulation could reduce Cr (VI) by 90.4% at pH 5, 24 V electrical potential, 24 minute hydrolysis time, and 13.7 kWh/$m^3$ electrical energy. The results for optimization were compared using coefficients of determination, where 0.8873 was produced with voltage × time and 0.9270 for amperage × time, while energy consumption was related to voltage × time (0.89490) and amperage × time is 0.9400 [24]. Salari *et al.* considered the process of peroxi-coagulation for the purpose of decolorization of C.I. Basic Yellow 2, when using a sulfate electrolyte media at 3.0 and a gas-diffusion electrode (GDE) as cathode. According to the results, 90% decolorization occurred within 30 minutes, while the artificial neural network (ANN) was proven to show how decolorization could be efficient under various constraints [25]. Zarei *et al.* considered the treatment of four dyes within an aqueous solution—C.I. Basic Blue 3, Malachite green, C.I. Basic red 46, and C.I. Basic Yellow 2 at pH 3 using a carbon

nanotube polytetrafluoroethleyene (CNT-PTFE) as cathode. From the experiment, 90% decolorization was determined within 10 minutes through modeling using the artificial neural network model. From the model, an $r^2$ value of 0.989 was produced for decolorization. Also, TOC for C.I. Basic Yellow was removed at 92% and mixed dyes at 93% within 6 hours. Compared with the real wastewater, 95% removal of Basic Yellow 2 and mixed dyes had a 90% removed within 40 minutes [26].

Hu *et al.* concluded that current density, initial pH, electrolyte species, initial concentration of dye produce the effects upon the removal of C.I. Reactive Red 241 by electrocoagulation in regards to decolorization. From the results, it was determined that dye removal was a first order reaction, where the COD removal could be determined using the artificial neural network (ANN) and response surface method (RSM) models [27]. Cai and White prepared a model for simulation of reducing Cr(VI) by ferrous iron anode through electrocoagulation using electrochemical and homogenous reactions. The parameters considered including material feed velocity, support electrolyte concentration, and cell potential on Cr(VI) conversion [28]. Zhu *et al.* concluded that a homemade reactor known as coagulation-electrocoagulagtion technology for thrice oilfield sewage where removal is 69.3% COD with pH is 7, aluminum sulfate dosage is 300 mg/L, rotational speed at 500 r/min for 30 minutes, current density of 12.5 $A/m^2$, and temperature 40 Delta DGC [29].

## 4. Decolorization

Kuleyin and Balcioglu concluded that by removing crystal violet by electrocoagulation under various pH values, 99% color was removed at pH within 10 minutes electrolysis time. When current density was increased from 5.8 to $mA/cm^2$, there was a 40% increase in removal. Also, color was removed with an efficiency of 95% for an initial concentration of 90 mg/L, while 55% removal was observed when the concentration was 570 mg/L [30]. Zhang *et al.* determined that 97% color removal was obtained after 10 minutes electrolysis time, with an electrical potential of 20 V, current of 0.4 A, electrode distance of 2.5 cm, concentration of 500 mg/L, KCl concentration of 0.5 g/L , and a pH of 3.0 for the purpose of treating methyl orange simulate dye wastewater by electrocoagulation. The authors were able to construct a model in which coagulation was determined for $COD_{Cr}$ removal followed by oxidation [31]. Kabdaşlı *et al.* noticed that color abatement can use stainless steel electrodes for electrocoagulation of reactive dyebath effluent. The most effective treatment was using $Na_2CO_3$ for color and COD removals, while NaCl concentration solved the problems when using $Na_2CO_3$ by better enhancing color and COD removal efficiencies when pH was above 11 for coagulation and adsorption [32]. Jain *et al.* concluded that azo reactive dye, a component from color paper, plastic, food, and pharmaceutical products are difficult to treat with conventional treatment methods due to water solubility and polar compounds [33]. Yang determined that decolorization of reactive dye was high affected by current density, pH, temperature, dye concentration, and NaCl was optimal at 88%, pH between 4 and 9, and NaCl was the major factor within decolorization [34].

Ghosh *et al.* observed a 99.75% crystal violet removal by electrocoagulation when initial treatment concentration was 100 mg/L, current density 1,112.5 $A/m^2$, solution conductivity of 1.61 S/m, pH of 8.5, and 1 hour of electrolysis time. It was also noticed that the cost for optimum treatment was 0.2141 $US\$/m^3$ [35]. Sengil and Ozacar removed 98% of color at dye concentration of 100 mg/L, pH of 5, current density of 45.75 $mA/cm^2$, salt concentration of 3,000 mg/L, temperature of 20 degrees

Celsius, and inter electrode distance of 2.5 cm. Also, results showed an energy consumption of 4.96 kWh/kg dye using a first-order equation [36]. Chen *et al.* completed a laboratory scale experiment considering dyestuff by pulse electrocoagulation, having considering the parameters of pulse duty factor, frequency, current density, and electrolysis time. It was determined that energy and electrode consumption was improved over direct current (DC) electrocoagulation [37]. Bellebia *et al.* discovered that Marine Blue Erionye MR dye and Brilliant Blue Levafix E-BRA (reactive dye) could be removed successfully under 7.46 and 1.49 $F/m^3$ loading and abatement at a concentration of 200 mg/L. Reactive dye Brilliant Blue Levafix E-BRA was completely removed during adsorption of 700 mg/L granular activated carbon (GAC) [38]. Ahlawat *et al.* determined that cotton blue acid dye by means of electrocoagulation using aluminum electrodes could be removed at a 97% efficiency, provided pH was 6, electrolysis time of 15 minutes, and an initial concentration of 100 mg/L, and applied voltage of 11. In addition, the authors determined that electrocoagulation was capable of degrading sludge suitable for disposal [39]. Liu *et al.* determined by using electrocoagulation, Eriochrome Black T simulated dye wastewater was degraded considering the following parameters—space of plates, electrolysis time, electrolysis concentration, current density, and pH. Optimum conditions are plates at 2.5 cm, NaCl 1.0 g/L, density of 5 $mA/cm^2$, and pH 5.5. It was observed that 98% decoloration was determine, where the energy consumption was 2.76 kWh/kg [40].

Murthy and Raina found that navy blue-3G by means of electrocoagulation considered the following parameters—concentration, type of electrode, turbidity, voltage, pH, and time. Decolorization removal was 95% and 93% using aluminum and iron electrodes respectively [41]. Maghana *et al.* concluded that BOD, COD, and conductivity were capable of being removed by electrocoagulation within tea effluent. Using effluent from the Chemomi tea factory in Rift Valley, Kenya, the authors were capable to reduce COD by 96.6%, BOD by 84.0%, and conductivity by 31.5% and increase pH by 10.32%. The optimum parameters were electrical potential of 24 V, interelectrode distance of 5 mm, effluent volume ratio of 18.2 $m^2/m^3$, and a pH of 6. Electrocoagulation oxidized phenol tea color pigments that were ionization of iron in the pigments, form radicals, and phenols of long chains [42]. Song *et al.* determined that 96% of colored and 80% TOC was removed by an ozone electrocoagulator with an optimum pH of 10, dye concentration of 100 mg/L, current density of 10 $mA/cm^2$, salt concentration of 3,000 mg/L, temperature of 30 degrees Celsius, ozone flow rate of 20 mg/L, and electrode distance of 3 cm [43]. Sengil *et al.* were able to decolorize 98% of Reactive Black 5 from synthetic wastewater by using electrocoagulation with iron electrodes. Optimum conditions for treatment include dye concentration of 100 mg/L, pH of 5, current density of 4.575 $mA/cm^2$, salt concentration of 3,000 mg/L, temperature of 20 degrees Celsius, and inter electrode distance of 2.5 cm. The authors also observed electrical energy consumption of 4.96 kWh/kg dye [44].

Zidane *et al.* concluded that by testing various NaCl concentrations as an electrode by a factor of ten (1.5 and 1) from $10^{-3}$ to $10^{-2}$, electrocoagulation could treat CI Red Reactive 41 at best between 41 and 96% removal efficiency, where the absorption was at 540 nm through 60 minutes of treatment, where concentration ranges between 100 and 400 mg/L. At the 400 mg/L concentration, 88% absorption occurs within 10 minutes, as compared to 60% when using direct coagulation using an electric potential of 10 to 15 V. However, 100% removal could be achieved when using electrochemical treatment [45]. Kalyani *et al.* determined that COD removal was 95% and color removal was 92% when using mild steel, and 89% color and COD removal for aluminum electrodes

when attempting to treat pulp and paper industrial effluent. When it was combined using electrocoagulation with a sequential batch reactor, Langumir and Radke-Paushitz isotherm models were used for an adsorption isotherm [46]. Merzouk *et al.* concluded that COD removal was greater than 80% and color 85% when considering synthetic textile wastewater using aluminum electrodes, a COD 2,500 mg/L dye concentration was reduced to less than 200 mg/L, a pH between 6 and 9, residence time of 14 minutes, current density of 31.25 $mA/cm^2$, and water conductivity of 2.4 mS/cm at an electrode distance of 1 cm [47]. Essadki *et al.* concluded that 80% COD and color as a function of current density. Additional efficiency specific energy and electrode related to current, electrode gap, and conductivity. This can be achieved by using pollutant flotation and recirculation with $H_2$ microbubbles by water electrolysis. This was achieved using red dye from Moroccan textile using a 20 L external loop air-reactor with a batch electrocoagulator [48]. Hanafi *et al.* compiled a study on olive mill wastewater treatment considering modifying COD, polyphenols, dark color removal, and pH. Through an optimum time of 15 minutes, 2 mg/L of $Cl_2$ concentration, pH of 4.2, and density of 250 $A/m^2$ , polyphenols were reduced by 70%, electrode composition is 0.085kg Al/kg $COD_{remoced}$, and energy concsumption 2.63 kWh/kg $COD_{removed}$ [49].

Balla *et al.* studied the efficiency of an electrocoagulation/electroflotation had a 90% removal rate of color with synthetic mixture as compared to 78–90% removal of color in textile wastewater by providing mixture of Red S3B 195, Yellow SPD, Blue BRFS, Yellow Terasil 4G, Red terasil 343, and Blue terasil 3R02. In addition, electrical energy for mixture dyes was high energy requirement than the two other dyes [50]. Animes *et al.* concluded that application of an electrocoagulation process, color was removed between 90 and 98% when operating the apparatus for one hour treatment of trypan blue, orange G with electrodes made from mild steel and aluminum electrodes. Additional effects involved higher density currents and pH [51].

## 5. Wastewater Treatment

### *5.1. Domestic Wastewater Treatment*

Yang *et al.* studied the electrocoagulation electroflotation processes and noted that high COD removal could be achieved; however, suspended solids and color removal was not conducive for secondary sewage treatment; nevertheless, electrocoagulation could be used for small scale, decentralized municipal domestic sewage treatment [52]. Illhan *et al.* concluded that COD and SS could be removed at 60 and 70%, respectively, from domestic wastewater at the Istanbul-Yenikapi Domestic Wastewater Treatment Plant with electrocoagulation using iron-iron electrodes. Operating parameters included 0.6 W electrical power, electrolysis time of 15 minutes for heavy load (380 mg COD/L) and 8 minutes for weakly loaded (260 mg COD/L). It was determined that electrical charge conditions were 0.4 $kWh/m^3$ for heavy loads, and 0.2 $kWh/m^3$ for weakly loaded. Sludge production was between 1.5 and 2%. [53]. Bukhari was capable of removing 95.4% TSS treatment efficiency with a current of 0.8 A and a contact time of 5 minutes using an electro-coagulator with stainless steel electrodes. The pattern is noticed was a sweep-floc coagulation where soluble ferrous ions were changed to insoluble ferric ions by oxidation with chlorine. Also, the BOD had a profound effect on the TSS removal in the presence of particulates [54]. Rodrigo *et al.* is capable of removing

ionic phosphorus and COD, when using conductive-diamond electrochemical oxidation and electrocoagulation for persistent organic consumption, specifically regeneration of urban wastewater. The study stated that energy consumption is capable of removal at values lower than 4.5 kWh/$m^3$ [55].

### *5.2. Industrial Wastewater Treatment*

Zongo *et al.* determined that by using electrocoagulation for textile industry wastewater with aluminum and iron electrodes, the authors concluded that that the important parameters—energy consumption where COD, turbidity abatement, electrode material, current efficiency, and cell voltage. Absorbance and COD had similar variations along the treatment, where a model could relate metal dissolution and pollution substance [56]. Linares-Hernandez *et al.* determined that 99% COD, 100% color, and 100% turbidity was removed by a two-step process—electrocoagulation with iron electrode and electrooxidation with a boron dipped diamond electrode [57]. Augustin determined that electrocoagulation aws capable of reducing turbidity, acidity, BOD, COD, and heavy metals within palm oil mill effluent from Chumporn Province in Thailand using aluminum electrodes and NaCl as electrolyte. Also, electrocoagulation was determined to have a strong recovery in these various components [58]. Wang and Chou concluded that COD concentration could be reduced to value greater than 90% by electrocoagulation, below the Taiwan discharge standard of 100 mg/L, provided that the concentration of chemical mechanical polishing wastewater was 200 mg/L NaCl, electrical potential of 20 V, and temperature of 25 degrees Celsius. With a 90% removal, it was noted that the water could be capable of being for possible reuse. Also, the kinetic study would reflect a pseudo-first kinetic model [59]. Espinoza-Quinones *et al.* concluded that by treating leather-finishing processes using an electrocoagulation process using aluminum electrode plates under a pH of 7.6 and an electrolysis time between 30 and 45 minutes, the treatment efficiency for COD, turbidity, total suspended solids (TSS), total fixed solids (TFS), total volatile solids (T*VS.*), and chemical effluent concentration. This was confirmed through analysis of variance (ANOVA) with a 95% confidence level [60].

Zhang *et al.* concluded that considering the use of organiochlorine pesticide contamination and found that a presence of pesticides within those soils. In addition, the authors suggested that human population within the vicinity of the soils were under a threat to being exposed to those pollutions, as it required treatment technologies to rid those pesticides from the soils [61]. Asselin *et al.* concluded that total suspended solids (TSS) was removed at 89%, turbidity 90%, BOD 86%, and oil and grease 99%, when completing electrocoagulation by combining mild steel or aluminum electrodes for treating slaughterhouse wastewater. In addition, it was identified that the total cost of treatment is 0.71 USD/$m^3$ treated poultry slaughterhouse (PS) effluent, particularly including energy and electrode consumption and chemical and sludge disposal [62]. El-Naas *et al.* concluded that through batch experiments it was proven that the most effective treatment for petroleum refinery wastewater was using aluminum electrodes. Factors that were discussed included current density and initial concentration of the wastewater, where the temperature was 25 degrees Celsius and pH of 8 [63]. Khansorthong and Hunsom were able to reduce color and COD by 91% and 77%, respectively, with operating costs of 0.29 USD/$m^3$ wastewater when treating pulp and paper mill by electrocoagulation in batch mode with 6 iron mate pieces. For continuous electrocoagulation, 91% color and 77% COD reduction was

completed in 2.15 hours were first order kinetic was the model for filtering of choice. Also total BOD, COD, TSS, TDS, pH, and color were acceptable for Thai Government Standards [64].

Chatzisyneon *et al.* concluded that by using electrochemical oxidation of olive mill wastewater (OMW) with a $TiO_2$ anode, it was noticed that the oxidation of OMW at 43 Ah/L, 80 degrees Celsius, and 5 mM NaCl can completely remove color, phenols, ecotoxicity, and low 30% COD removal with a 50 $A/cm^2$ current density [65]. Oelmez-Hanci *et al.* concluded that COD in olive mill wastewater was reduced by 30% and 20% TOC when using $UV_{254}$ and $UV_{280}$ analysis. Effects were noticed based on pH and coagulant/polymer dosages, Fenton treatment is based on pH and Fe(II) concentrations, steel electrodes at various concentrations, and current densities [66]. Raju *et al.* concluded that COD would be reduced from 1,316 mg/L to 42.9 mg/L when using electrocoagulation for the purpose of treating textile wastewater. Treatment was completed using graphite and $RuO_2/IrO_2/TaO_2$ with titanium electrodes. Overall, electrooxidation noticed the effects of electrolyte type within relation to $Cl^-$ ions [67].

Espinoza-Quniones *et al.* concluded that pollutant removal was completely accomplished for COD, turbidity, and concentrations of chromium, provided that pH is neutral and electrocoagulation ranges between 30 and 45 min. In addition, experimental design is necessary to be a factoral fraction $2^3$, for a leather finishing industrial process wastewater for organic and industrial pollutant removal [68]. Zaied and Bellahkal determined that using a pH of 7, electrolysis time of 50 minutes, current density of 14 $mA/cm^2$, treatment of black liquor by elecrocoagulation removed 98% COD, 92% polyphenols, and 99% color [69]. Zaleska-Chrost *et al.* determined that laboratory conditions for electrocoagulation was a better treatment than chemical coagulation, having identified COD, turbidity, suspended solids, and color, where crude sewage is contingent on the pollutant removal efficiency [70]. Tezcan Un *et al.* concluded that electrocoagulation with aluminum electrodes was capable of successfully treating vegetable oil refinery wastewater with aluminum electrodes. Within the study, the authors considered optimum conditions for pH, poly-aluminum chloride (PAC) and $Na_2SO_4$ dosage. The concluding value was that 98.9% COD was removed in 90 minutes, where the current density was 35 $mA/cm^2$ and energy consumption of 42 kWh/kg COD removed [71]. Sengil *et al.* determined that COD (82%), sulphide (90%), and oil-grease removal (96%) from tannery liming drum wastewater by electrogoaluation. Optimum parameters for treatment were 35 $mA/cm^2$, 10 minutes electrolysis time, pH of 3, near energy consumption of 5.768 $kWh/m^3$ COD, 0.524 $kWh/m^3$ sulfide, and 0.00018 $kWh/m^3$ oil-grease. Kinetics from the experiment produced a pseudo-second order rate equation [72]. Desphande *et al.* concluded that bulk drug industry wastewater COD could be removed at 34%, with a $BOD_5$/COD ratio of 0.581 at 120 treatment time, when using the electrochemical method. The optuimum parameters include 95.83 kWh/kg energy consumption and an anode efficiency of 5.76 kg COD/$Am^2h$ [73]. Linarez-Hernandez *et al.* observed that the combination of electrocoagulation and electroxidation was capable of successful at complining treatment—electrocoagulation coagulates and removes particulates, while electrocoagulation oxidizes what remains. Overall, the process is capable of reducing COD, $BOD_5$, color, turbidity, and coliforms in 2 hours [74].

Wang *et al.* was capable of removing 62% COD when using ultrasound for electrocoagulation. Nevertheless, higher removal efficiency of COD is capable with optimum conditions of 5 V electrical potential, chlorine contact less than 2,500 ppm, two aluminum electrodes and a 999 $mg/dm^3$ kWh amount per joule, where the treatment was contingent on the amount of aluminum plates present [75].

Wang *et al.* concluding that by using iron and aluminum electrode pair, 200 ppm NaCl, 30 V of electricity, silica particles and turbidity reduction is feasible from oxide chemical mechanical wastewater with a particle size produced was between 520 and 1,900 nm as the time range was between 10 and 20 minutes [76]. Merzouk *et al.* determined that 85.5% SS, 76.2% turbidity, 88.9% BOD, 79.7% COD, and 93% color could removed by the combination of electrocoagulation-electroflotation after ensuring optimum conditions for 300 mg/L silica, current density of 11.55 $mA/cm^2$, pH of 7.6, conductivity of 2.1 mS/cm, treatment time of 10 minutes, and electrode gap of 1 cm. The study was to consider for the treatment of textile wastewater having studied the above optimum parameters [77]. Katal and Pahlavanzadeh determined that by using aluminum and iron electrodes for electrocoagulation, optimum pH between 5 and 7, current density of 70 $mA/cm^2$ was capable of efficiently treating the wastewater at a low cost. In addition, temperature relationship also poorly affects the performance [78].

Meas *et al.* determined that by using an electrocoagulator with sacrificial electrodes, where COD (95%), color (99%), and turbidity (99%) can be reduced when testing fluorescent penetrated liquid for non-destructive testing of parts, where the water was reused 4 times [79]. Aoudj *et al.* determined that decolorization can be achieved at 98% under the optimum condition of a pH of 6, 1.875 $A/cm^2$ current density, inter-electrode distance of 1.5 cm, and NaCl electrolyte when removing Direct Red 8 from synthetic wastewater treatment [80]. Monghadam and Amiri concluded that by using a current density of 75 $A/m^2$, pH of 4, and conductivity of 3 mS/cm were capable of removing TOC from a phenol-formaldehyde resin manufacturing wastewater by electrocoagulation with aluminum electrodes [81].

### *5.3. Heavy Metals*

Bazrafshan *et al.* determined that Cr(VI) reduction from synthetic chromium solution could be under legal limits as long as treatment was between 20 and 60 minutes, a range for electric potential of 20 and 40 V, and a pH of 3. Also, the authors determined that chromium removal efficiency was better with iron electrodes than aluminum [82]. Bing-Fang discovered that by using a room temperature of 25 degrees Celsius, iron and stainless steel electrodes, a voltage and a pH of 4, and a $Na_2SO_4$ concentration of 0.7 mg/L, and an electrolysis time of 30 minutes, electrocoagulation could treat a simulated wastewater with $Cu^{2+}$ and $Cr^{6+}$ removal of 93% and 98.91 effectively [83]. Hansen *et al.* concluded that a 1 L airlift electrocoagulator could reduce arsenic concentration by 96% (1000 mg/L to 40 mg/L) by iron electrodes. Results indicated that the oxidation of $Fe^{2+}$ to $Fe^{3+}$ determined arsenic removal efficiency for arsenic concentration greater than 500 mg/L, whereas 98% arsenic removal was obtained for arsenic concentration of 100 mg/L. Also, the rate of removal was 0.08–0.1 mg As/C, where Fe-to-As ratio (mol/mol) was about 486 [84]. Qui *et al.* concluded that having a pH of 4, voltage 2.5 V, hydraulic retention time of 15 minutes, current density of 25 $A/m^2$, removal rate could be achieved at 99.5%, when treating electroplating wastewater by pulse electrocoagulation [85].

Belkacem *et al.* concluded that $BOD_5$ removal was 93.5%, COD 90.3%, turbidity 78.7%, suspended solids, and color greater than 93% using electrofiltration with aluminum electrodes, where parameters involved electrical potential of 20 V, distance of 1 cm, and electrolysis time less than 20 minutes. Also, the kinetics was less than 5 minutes with a removal of 99% [86]. Rayman and White concluded that by using a parallel-plate electrochemical reactor, the reduction of Cr(VI) using Fe(II) as the anode, the

space velocity must remain at 0.02 $s^{-1}$. It was also imperative to increase the current density by means of the current potential, the supporting electrolyte, decrease the distance between the electrodes for proper conversion; however, if one were to decrease the current density, the specific energy requirement increased [87]. Heidmann and Calmano was capable of treating galvanized wastewater by successfully reducing heavy metals of Cr and Cu by over 99% and 90% of Ni, as long as optimum conditions of a PH were greater than 5, 0.2 A for Fe electrodes, 1.5 A for Al electrodes, and a power consumption of 9.0 kWh/$m^3$ [88]. Deniel *et al.* determined that by using iron and hybrid Al/Fe electrodes for electrocoagulation, the electrodes were capable of reducing the arsenic concentration by 99%, as the current density was increased from 0.0082 to 0.0816 mA/cm [89].

Nouri *et al.* concluded that electrocoagulation had a treatment time between 20 and 60 minutes, 40 V electrical potential for the removal of Cr(VI) ions by using iron electrodes, and a pH of 3 [90]. Wu *et al.* compared the use of electrocoagulation with aluminum and iron electrodes in combination with UV/$TiO_2$ and ozone. It was determined that decolorization efficiency could be rincreased by combining UV/$TiO_2$ or UV/$O_3$, and it was able to reduce power requirement to 8 W. Also, pH was increased to 7.4 as well. What was also observed was that treatment followed pseudo-first order kinetics [91]. Heidmann and Calmano reported that the parameters affecting electrocoagulation process included the chromium concentration, charge loading, and current concentration. Cr concentration decreased slightly by coagulation time at high currents (1.0–3.0 A), whereas at low currents (0.05–0.1 A), 10 mg/L Cr was removed completely from the solution after 45 min [92]. Thella *et al.* concluded that electrode, water current, and gap affected the overall efficiency in treating for arsenic and chromium by a batch electrocoagulation [93]. Optimum conditions found were that the value of pH was 4.0 for arsenic removal and 2.0 for chromium, current density of 75 A/$m^2$ for arsenic and 50 A/$m^2$ for chromium and a stirring rate value of 100 rpm. Petsriprasit *et al.* determined that Cu, Cr, Pb, and Zn from billet industry wastewater was capable of being removed by 99%, where it was found that density current is 98 A/$m^2$, pH of 5, and 30 minutes electrolysis time. It was noticed that within 120 minutes, pH of 3, and flow rate of 55 mL/min could obtain similar values [94].

Shafaei *et al.* was capable of removing $Mn^{2+}$ ions by electrocoagulation with aluminum electrodes under an optimum pH of 7.0. Factors concluded by the authors were the density and electrolysis time, along with initial concentration were capable of determining successful removal rates [95]. Vansudervan *et al.* was capable of removing arsenate by electrocoagulation with aluminum alloy as anode and stainless steel as a cathode. The removal efficiency was 98.4%, current density of 0.2 A/$dm^2$, and a pH of 7.0. Arsenate adsorption could be fitted into a Langumir adsorption isotherm with first and second order rate equations [96].

### *5.4. Organic and Inorganic Removal*

Mahvi *et al.* concluded that sulfate removal was best removed whenever the electrical potential was 30 V, reaction time 60 minutes, and pH of 11 when using a six-plate aluminum electrode electrocoagulator. Initial concentration was also an important factor as the authors considered treatment at 350 and 700 mg/L concentrations [97]. Kongjao *et al.* determined that chromium and pollutants could be removed within 95% by considering tannery wastewater with a one-step electrocoagulation process. Additional parameters included a pH between 7 and 9, current density of

22.4 A/$m^2$, flow of 3.67 L/min, and 20 minute electrolysis time. Energy consumption was reported as being 0.13 kWh/$m^3$ and a first order kinetics model for COD removal [98]. Kumar *et al.* concluded that COD and color removal was 50% and 95.2%, respectively, at optimum conditions for treatment of bio-effluent wastewater using electrocoagulation. Parameters to consider included current density between 44.65 and 223.25 Am/$cm^2$, pH between 2 and 8, inter-electrode distance of 1 and 3 cm, and electrolysis time between 30 and 150 minutes. It was determined through ANOVA analysis the $r^2$ value was 0.8547 [99]. Barrea-Diaz *et al.* concluded that COD (92%), BOD (89%), color (92%), turbidity (95%), and total coliform (99%) when adding hydrogen peroxide to electrocoagulator using aluminum and iron electrodes to treat a complex wastewater consisting of organic compounds [100].

Bhaskar Raju *et al.* determined that COD was removed between 90 and 93% by graphite, 54% by $RuO_2/IrO_2/TaO_2$ coated titanium electrodes, when using various electrochemical methods for treating textile wastewater. The treatment method was electrocoagulation by steel electrodes for suspended solids and electroxidation for COD removal for the purpose of pretreatment method to reverse osmosis [101]. Yilmaz *et al.* studied the removal of boron from synthetic wastewater having considered pH as an optimum at 8.0. After looking at the resin/boron solution, boron concentration, stirring speed, and temperature, 99% removal occurred, where the boron removal rate was affected by stirring speed and temperature—increasing the speed, decreased the floc formulation and removal; increasing the temperature increased the boron removal. The authors developed a pseudo-second order model equation based on the heterogeneous fluid-solid reaction [102]. Xu *et al.* determined that by using multi-staged electrocoagulation, 99% removal from boron concentration was completed after the fifth stage taking the concentration from 500 mg/L to less than 0.5 mg/L under a current density of 62.1 A/$m^2$ [103]. In addition, the authors noticed that arsenic removal was successful in reducing the concentration from 15 mg/L to 0.5 mg/L. Hansen and Ottosen suggested that reason electrocoagulation is a suitable treatment for arsenic removal because of its ability to precipitate hydroxide-arsenic compounds. However, $Ca(OH)_2$, prior to successful removal of arsenic required additional treatment [104]. Khatibikamal *et al.* determined that pH between 6 and 7, when using electrocoagulation with aluminum electrodes,was optimal for treatment, where the pH would be reduced over time, number of plates had no effect, and second rate kinetics model was concluded for absorption. Fluoride was reduced from 4 to 6 mg/L to 0.5 mg/L [105].

### *5.5. With Photolysis Degradation, Advanced Oxidation*

Boroski *et al.* concluded that electrocoagulation filtration combined photocatalysis using a $UV/TiO_2/H_2O_2$ systems improved the biodegradable index (BOD/COD) from 0.48 after electrocoagulation to 0.89 with the use of the hybrid system, using 6 hours photocatalysis irritation, provided a 30 minute EC/$Fe^0$, 153 A/$m^2$, pH of 6.0. A COD reduction was 88% in the system, provided 50 mmol/L $H_2O_2$ and an additional NaCl concentration of 5.0 g/L reduced electrolysis time from 30 to 10 minutes [106]. Apaydin and Gonullu *et al.* concluded that COD and sulfide were capable of being removed at 46% and 90% during electrocoagualtion, whereas electro-Fenton was efficient in removing 54% and 85%, when treating tannery wastewater using iron electrodes. Operating parameters for the treatment process included electrical current of 33.3 mA/$m^2$, electrical consumption of 1.5 kWh/$m^2$ COD removal and 8.3 kWh/kg $SO_4^{2-}$ removed [107]. Parga *et al.* developed a

technique by using electrocoagulation as a method was very important as the photocatalysis degradation of cyanide by $TiO_2$ required particle fineness; so using electrocoagulation for recovery has a 93% recovery rate. Also it was determined that the Langmuir isotherm procedures developed included (free energy value) $\Delta G^0$ = −37 kK/mol, enthalphy ($\Delta H^0$ = −54 kJ/mol) and entropy ($\Delta S^0$ = 0.524 kJ/mol), where $TiO_2$ is 93% in 30 minutes electrolysis time and using a 50 W halogen lamp [108]. Rodrigues *et al.* observed 91% turbidity and 86% COD removal, going from 1,753 to 60 mg/L using strictly electrocoagulation, while reduction was capable at 50 mg/L when using electrocoagulation combined with photocatalysis using titanium dioxide for treating pharmaceutical wastewater. Optimum conditions included iron electrodes, current density of 763 A/m$^2$, 90 minute treatment time, and pH of 6, whereas photocatalysis ($UV/TiO_2/H_2O_2$) consisted of a pH of 3, 45 irritation, 0.25 g/L $TiO_2$, 10 mmol/L $H_2O_2$ [109].

Tezcan Un *et al.* concluded that by using a hybrid electrocoagulation with iron and aluminum electrodes and $Na_2SO_4$ and a pH of 7.8, the treatment process was capable of removing 94.4% COD of an initial concentration of 1,200 mg/L. The optimum parameters included a polyaluminum coagulation with 0.75 g/L PAC concentration. The treatment met slaughterhouse wastewater treatment standards in Turkey. Also, combined with the Fenton process, 81.1% COD was removed with 9% $H_2O_2$ [110]. Canizares *et al.* concluded that the use of a boron doped diamed (BDD) anode for soluble organic matter mineralization was capable of breaking down metalworking wastewater by physio-chemical processes using an electrochemical reactor [111]. Li *et al.* concluded that oil removal rate from oilfield wastewater using an electrocoagulator with sacrificial aluminum electrodes was capable of removing 89.6%, where the current intensity is 1 A, plate spacing of 10 mm, initial oilfield concentration is 500 mg/L, pH 7.2, and electrolysis time of 20 minutes [112]. Zhang *et al.* decolorized CI Acid Red 2 on a platinum rotating disc resulting in a 98% reduction within 40 minutes by using an electrogenerated iron hydroxide from eelctrogenerated ferrous irons, where decolorization was combined with electrocoagulation electro oxidation procedures [113]. Hernandez-Ortega concluded that turbidity by color at 90% and COD by 60% when using a combined electrocoagulation-ozonation process with wastewater from 140 factories. This process was suitable to treat industrial wastewater prior to the biological process of wastewater treatment [114].

### *5.6. Combined Treated with Adsorption, Membranes*

Narayanan and Ganesam observed that chromium (VI) removal can be achieved by the combination of electrocoagulation and granulation activated carbon (GAC) at a pH of 8. The optimum conditions would be considered when the current density has been increased to 26.7 mA/cm$^2$, operating time of 100 minutes for the electrocoagulation. The authors noticed that with GAC added to the systems it dramatically reduced the concentration of chromium [115]. Yüksel *et al.* determined that sodium doecyl sulfate (SDS) removal was 81.6% for peroxi-electrocoagulation, where the optimum conditions included 60 mg/L, 0.5 mA/cm$^2$, 10 minutes electrolysis time, and an energy consumption of 1.63 kWh/kg SDS. In addition, pseudo-second order equation was observed [116]. Kumarasinghe *et al.* concluded that for a model wastewater consisting of copper, lead, and cadmium, the removal was contingent and electrolysis time, current density, and solution pH when using a hybrid

electrocoagulation-ultradfiltration system. The authors concluded that removal was greatly affected by maintaining a non-acidic pH [117].

Aouni *et al.* discovered that COD, turbidity, and color could be removed from textile wastewater using electrocoagulation with nanofiltration. The parameters considered included current densities and experimental tense. For each treatment process, electrochemical treatment was for color and COD, while nanofiltration for color, COD, alkalinity, conductivity, and total dissolved solids (TDS) [118]. Yang and Tsai concluded that electrocoagulation/electrofiltration treatment with carbon filters and carbon/alumina tubular composite membranes was successful in treating chemical mechanical polishing of the copper layer (Cu-CMP) wastewater with pore size between 2 and 20 mm and nominal pore size of 3.5 mm. The treatment led to an 82 to 91% TS removal, TOC removal, Cu, and Si removals [119]. Chang *et al.* combined electrocoagulation-activated carbon adsorption-microwave generation. Through electrocoagulation, 39% COD removal occurred with pH of 8, electrolysis time of 8 minutes, and a density of 277 $A/m^2$, and a NaCl contact of 1 g/L. The study produced favorable results with 100 g/L GAC that removed 82% of Reactive Black 5 (RB5) and with 20 g/L GAC that removed the remaining 61% of COD [120]. Chou *et al.* used electrocoagulation for removal of COD in oxide CMP wastewater, where it was determined that COD could be reduced by 90%. Also, the authors determined that this process followed pseudo-second order under the Freundlich adsorption isotherm model at various densities and temperatures [121]. Lakshmanan *et al.* concluded that arsenic was removed by 98% when using NaCl, and was removed by 75% when using sodium sulfate and nitrate during a 5 minute appearance and an initial concentration of wastewater of 10 mg/L within the electrocoagulator. Adsorption was affected by several factors, including magnetic, particle size, and surface properties of the precipitate; solid waste from the treatment was non-hazardous [122].

### *5.7. Combined with Aerobic, Anaerobic Processes*

Yetilnezsoy *et al.* discovered a 90% COD and 92% color efficiency by electrocoagulation from an upflow aerobic sludge blanket reactor with aluminum and iron electrodes. It was also determined that aluminum electrodes were more efficient for treatment. Optimum conditions would be a pH of 5, current density of 15 $mA/cm^2$, and an electrolysis time of 20 minutes [123]. Barrea-Diaz *et al.* concluded that COD was removed at 68% when combining with electrochemical and biological treatment for the removal of complex industrial wastewater using aluminum reactor. These treatment efficiencies improved recalcitrant concentrations in the wastewater as compared to biological whereas COD only reduced treatment by 30%. Also, the authors noticed that if aluminum polyhydroxychloride (PAC) coagulant was added at a rate of 4 $mL/dm^3$ along with a batch electrochemical reactor, it would greatly improved COD and color results [124]. Basha *et al.* proved that the combination of electrochemical degradation and biological oxidation was capable of reducing COD by 80% from 48,000 mg/L to 17,000 mg/L from the organic industrial wastes. The microorganisms used were *Baciliu subtillis*, *Pseudomones aeruginosa*, and *Proteus vulgaris*. It was concluded that the water could be reused following experiments [125]. Desphande *et al.* concluded that using a combined electrocoagulation and anaerobic fixed film reactor, COD, BOD, and color could be removed at 24%, 35%, and 70%, respectively, with conditions of pH at 7.2, current density of 80 $A/m^2$, and electrolysis time of 25 minutes for mere electrocoagulation. However, when combined with the anaerobic fixed

film reaction, removals increased to 80–90% COD, 86–94% BOD, at 0.6 to 4.0 kg COD/$m^3$s organic loading rate [126].

Phalakornukule *et al.* concluded that treatment of Reactive Blue 140 and Direct Red 23 required electrical energy of 1.42 and 0.69 kWh/$m^3$, respectively, with color (99%), COD (93%), and TS (89%) removal, when using a continuous electrocoagulation. In addition, the authors were able to harvest hydrogen [127]. Moises *et al.* conducted study to remove color (94%), turbidity (92%), COD (80%) for industrial wastewater at a flow rate of 50 mL/min [128].

### *5.8. Dye Removal*

Wang *et al.* determined that high removal efficiency of orange G simulated dye could be achieved, when the pH was 4.5, NaCl concentration was 0.75 g/L, space between electrodes was 10 mm, treatment time 10 minutes. The authors observed no relation with the applied voltage [129]. Rahgu and Basha removed 100% COD and 92% color by the use of Ti/$RuO_2$/$IrO_2$ as anode and stainless steel as cathode within an electrochemical membrane for the purpose of treating textile dyebath and generate caustic soda, where the caustic soda generation went from 40 to 210.28 g/L [130]. Phalakorkule *et al.* reported a study for treating Reactive Blue 140 reactive dye and disperse dye II. Results indicated that color was reduced by 95% with an energy consumption of 1 kWh/$m^3$ and a dye concentration of 100 mg/L during synthetic treatment [131]. Mollah *et al.* removed 94.5% of orange II dye from 10 ppm at density of 160 A/$m^2$, pH of 6.5, conductance of 7.1 mS/cm, flow rate of 350 mL/min, and NaCl concentration of 4.0 g/L [132].

### *5.9. Pretreatment*

Arsten-Alaton and Turkoglu concluded that using aluminum and stainless steel electrodes for color and COD removal for disperse dyebath, treatment was able to remove color and COD instantaneously at a pH of around 7.0 for complete color removal and 61% COD removal for conditions of using 2,000 mg/L NaCl electrolyte and an electrical current density of 44 mA/cm. This process was compared to coagulation process which used aluminum sulfate as a coagulation between 200 and 2,000 mg/L, under a pH between 3.5–11.5 [133]. Khoufi *et al.* concluded that elctrocoagulation as pretreatment was very successful in treating olive mill wastewater by reducing toxicity and improved the performance of methanization as long as the oxygen loading rate was between 4 and 7.5 COD/day. Because of electrocoagulation, anaerobic digestion and particularly methanization improved COD removal to 80%. Aerobic treatment removed COD by 78.7%, and extraction of ethyl acetate was at 90% recovery [134].

### *5.10. Other Treatment*

Koparal *et al.* concluded that removal efficiency for humic substances in synthetically prepared wastewater within electrocoagulation using aluminum plate electrodes was related to the initial pH at 5 due to the presence of a gel layer formation on the anode surfaces. This was observed at high concentrations, where the concentration is greater than 120 mg/L [135]. Panizza and Cerisola was successful in removing 75% chemical oxygen demand (COD) from carwash wastewater by combining

electrocoagulation with iron anodes and electrochemical with boron-doped diamond anode. What was determined was a 2 $mA/cm^2$, pH of 6.4, electrolysis time of 5 minutes. What was noticeable was that energy consumption is 0.4 $kWh/m^3$ [136]. Yu *et al.* determined that chemical oxygen demand ($COD_{cr}$) and turbidity was removed by 57.8% and 88.2% ,respectively, as it was observed that $COD_{cr}$ reduced from 144.15 mg/L to 60.96 mg/L, where turbidity was reduced from 39.06 NTU to 4.61 NTU. Operating parameters included 25 V electric potential, electrolysis time of 10 minutes, and a pH between 7 and 7.5 for carwash wastewater treated by electrocoagulation-flotating-contact filtration process [137].

Liu *et al.* concluded that removing chlorophyll-a and UV-254 was 81% and 56%, respectively, while turbidity was recorded at a value less than 2.6 NTU when using an electrocoagulation-flotation treatment system for landscape wastewater [138]. Mao *et al.* observed that the treatment of bathing wastewater was most effective in using electrocoauglation-air flotation, Biological Activated Carbon, Membrane Bioreactor, and filtration/ultrafiltration-biological activated carbon processes [139]. Arslan-Alaton *et al.* was capable of achieving 100% color using current between 33 and 65 $mA/cm^2$ and the time within the elctrocoagulator using aluminum electrodes between 10 and 15 minutes. Also, it was noted that the electrical energy consumption was only 5 $kWh/m^3$ within an electrocoagulator for treating real reactive dyebath effluent. This was contrary to using stainless steel electrodes which consumed 9 $kWh/m^3$ of electrical energy [140]. Cano Rodriguez *et al.* concluded that using a photoremediation technique of having Myriophyllum aquaticum along with electrocoagulation and a current density of 45.45 $A/m^2$, and pH of 8 couild remove COD (91%), color (97%), and turbidity (98%) from mixed industrial wastewater [141].

## 6. Analytical and Instrumentation

### *6.1. Equipment*

Moreno *et al.* studied green rust significance within electrocoagulation by considering measuring pH at locations near iron electrodes and observed that electrocoagulation was related to components such as solubility. Having analyzed components such as metal and non metal removal, suspended solids, organic compounds, COD (chemical oxygen demand) and BOD (biochemical oxygen demand), the authors observed that iron electrodes were more successful than aluminum electrodes for durability and cost [142]. Eyvaz *et al.* used electrocoagulation with parallel aluminum electrodes in batch mode for comparing alternative pulse current (APC) and direct current (DC) for treating Dianix Yellow XCC and Procium Yellow. It was determined that the alternating pulse current was better in removal of TOC and dye treatment as compared with the DC power supply [143]. Wang *et al.* found that using a pulse frequency between 500 to approximately 2,000 Hz had an effect on treatment performance. Overall, pulse current was found to be better than direct current, reducing power consumption by 40 to 50% [144]. Wang *et al.* concluded that by using DC electrocoagulation, in a treatment time of 25 minutes, decolorization and COD removal was 75.45% and 84.62%, respectively. The authors discovered a relationship between an increase of pH and alkalinity with increase in temperature, and electrolysis time, while voltage was related to current [145].

### *6.2. Treatment Efficiency*

Hu *et al.* concluded that there was a relationship between flow rate and suspended solids in a continuous electrocoagulation-flotation system with aluminum electrodes—removal efficiency was decreased when flow rate was greater than 800 mL/min, increased at 200 mL/min. The authors concluded that the $r_{G/S}$ (gas-solid ratio) under 0.1 L/g was ineffective for flotation, while $r_{G/L}$ (gas-liquid ratio) over 0.4 discontinued the suspended solids removal, and in fact, increased suspended solids [146]. Abdelwahab *et al.* concluded a relationship between current density and pH for removal of phenol from oil refinery wastewater. It was determined that pH 7 and electrolysis time of two hours with electrocoagulation, that 97% of phenol was removed down to 30 mg/L. For petroleum wastewater, 94.5% of phenol was removed within 2 hours [147].

### *6.3. Electrical Properties*

Sasson *et al.* reported that ferric anode was dissolved in a pH range between 5 and 9, electric current between 0.05–0.4 A, where rates were dependent on pH and oxidation rates of iron. The values calculated were theoretical based on Faraday's law and what was observed was different because with the calculation of non-dissolution without current, additional electrons present with reactions outside the anode were placed in the calculation as important parameters [148]. Arslan-Altan and Turkoglu determined that alum was effective to remove color by 100% and COD by 64%. It was found that at optimum electrochemical conditions were 2,500 NaCl, pH 7, and current density is 44 $mA/cm^2$. 100% color and 58% COD were removed for Aluminum electrodes where total treatment time of 30 minutes, as compared with 100% color and 45% COD removal using 2,000 mg/L NaCl, pH of 7.3, and a current density of 44 $mA/cm^2$ with a 60 minute treatment time. The most optimum treatment for coagulation was alum as compared with ferrous sulfate and ferric chloride [149]. Mouedhen *et al.* concluded that electrocoagulation with iron and aluminum electrodes with hexavalent chromium by abatement with Cr(III), Fe(II), and Fe(III), where various anode/cathode configurations Fe/Fe, Pt Ti/Fe, Al/Al, and Pt Ti/Al were studied. Based on the results, Fe electrodes affected chromium removal by less than 5%, Fe(II) assisted in the removal where acid pH predominated [150]. Zongo *et al.* considered treatment of Cr(VI) by electrocoagulation using Al or Fe electrodes with a discontinuous system. The results showed that COD removal was not affected by Cr(VI) for aluminum electrodes, where for Fe electrodes there was delay ine COD removal. Also, it was determined that Cr(III) precipitation was due to $Fe(OH)_3$ compound. However, removal could be through electrogenerated Fe(II), air oxygen, and reduction at the ion cathode [151].

### *6.4. Operating Parameters*

Arslan-Alaton concluded that complete color removal and partial COD removal could be accomplished by using an electrocoagulation by using both aluminum and stainless steel electrodes were optimized. In fact, the authors noticed that electrical energy and sludge production rate was lower with stainless steel (8 $kWh/m^3$ and 700 $g/m^3$) as compared to aluminum (17 $kWh/m^3$ and 8,200 $g/m^3$) [152]. Zodi *et al.* determined several parameters considered when treating industrial wastewater. First, using electrocoagulation then settling, one can consider suspended solids, high

turbidity, and COD. Next, sludge data was compared with models, and then determined based on sludge volume index (SVI) for the optimum conditions [153]. Valero *et al.* determined that treatment of textile dye Remazol Red RB 133 by an electrocoagulator with a photovoltaic array configuration affected the power generated, where the major parameter flow ratio was controlled [154]. Canizares *et al.* concluded that pH had an overall effect on the treatment efficiency for electrocoagulation for synthetic oil-in-water emulsion and effluent from a door manufacturing facility [155].

### *6.5. Energy Requirements*

Sasson and Adin concluded that using electroflotation with a current of 0.4 A, followed by slow-mixing, and filtration to treat pure water with silica-chemical mechanical polishing was able to reduce energy requirements for filtration by 90%. Also, pH must remain above 7 since the permeate change colors due to iron residuals ($Fe^{2+}$ to $Fe^{3+}$) [156]. Sasson and Adin considered silica-CMP suspensions were pretreated by electrocoagulation at an electric current of 0.4 A, slow mixing, and filtration. Filtration energy was reduced by 90% whenever the pH was between 6 and 6.5, having noticed foul mitigation was on intensity and mechanisms, suspension pH and electroflocculation time [157]. Chou *et al.* concluded that by using an iron/aluminum electrode pair for electrocoagulation, 100 mg/L NaCl, 20 mg/L initial wastewater concentration, and 20 V voltage application, indium (III) can be successfully removed. In addition, removal kinetics followed a pseudo second-order reaction [158]. Chou *et al.* concluded that COD and turbidity were removed by 90% and 98%, respectively, within real oxide-chemical mechanical polishing wastewater by means of a batch electrocoagulator. The authors noted that additional conditions that were optimum included 200 mg/L of NaCl, 20 V application of voltage and 12 min electrolysis time [159]. Terrazes *et al.* determined turbidity removal was 92% with an energy consumption of 0.68 $kWh/m^3$ by using micro-electrolysis and macro-electrolysis electrocoagulation for tissue paper wastewater treatment [160].

## 7. Comparison

Canizares *et al.* determined that using electrocoagulation consisted of lower costs for small coagulant requirement, as compared with coagulation, whereas higher requirement may favor conventional coagulation for removal of pollutants [161]. Khataee *et al.* developed a hybrid study using Fenton, electrocoagulation, UV/Nano-$TiO_2$, Fenton-like, and Electro Fenton to remove C.I. Acid Blue 9, where 98% color was removed when the solution contained 20 mg/L, pH of 6, an electrolysis time of 8 minutes, and a current density of 25 $mA/m^2$. Electrocoagulation was the second highest in decolorization efficiency, behind Fenton in decolorization efficiency [162].

El-Ashtoukhy and Amin concluded that electrocoagulation was capable of removing 87% of acid green dye 50, as compared COD removal of 68% for electrochemical oxidation. Energy consumption was lower in energy consumption (2.8 to 12.8 kWh/kg dye, *versus* 3.31 to 16.97 kWh/kg dye) [163]. Kılıç and Hoşten compared electrocoagulation and coagulation and stated that coagulation could be more efficient around 5–8, as compared to electrocoagulation using aluminum hydroxide as a precipitate. Electrocoagulation was second order kinetics on less than 10 minutes [164].

## **8**. **Cost Analysis**

Having many treatment process options for wastewater treatment, it is necessary for electrocoauglation to be cost-effective. Kobya *et al.* found that the treatment of cadmium and nickel from electroplating rinse water could be achieved at 99.4% for cadmium, 99.1% for nickel, and 99.7% for cyanide. The cost for treatment was \$1.05/$m^3$ for cadmium and \$2.45/$m^3$ for nickel and cyanide provided that the treatment maintained optimum conditions [165]. Kobya *et al.* also studied Remazol Red 3B decolorization using iron electrodes and found that 99% decolorization was possible under optimum conditions. The authors found that energy consumption could achieve 3.3 kWh/kg dye at a cost of 0.6 euro/$m^3$ [166]. Meas *et al.* concluded that aluminum electrodes are capable of treating fluorescent penetrant liquid for non-destructing testing part of aircraft industry. Having used electrocoagulation, the treatment present found 95% of chemical oxygen demand (COD), 99% color, and 99% turbidity. With this high level of treatment, the cost were able to have a return of 17 weeks [167]. Asselin *et al.* experiment and analyzed oil bilge wastewater [OBW] at laboratory scale used iron and aluminum electrodes using bipolar (BP) and monopolar (MP) configuration. Using optimum conditions, treatment of oil bilge wastewater by electrocoagulation 93% biochemical oxygen demand, 95.6% oil and grease, 99.8% total suspended solids, and 98.4% turbidity. From this analysis, it was determined that the costs was \$0.46/$m^3$ of oil bilge treatment was for energy and electrode consumption, chemicals, and sludge disposal [168].

Ghosh *et al.* used electrochemical using aluminum electrodes for the purpose of removing iron [Fe(II)] removal from tapwater having considered amorphous aluminum hydroxides, current densitites, and electrode density. From the experiment, the authors found that when treating a concentration of 15 mg/L Fe(II) concentration, it would cost \$6.05 USD/$m^3$ of tapwater [169]. Drogui *et al.* used electrocoagulation with mild steel electrodes treating agro-industry (meat processing, cereal, and food beverages) wastewater. Considering chemical oxygen demand (COD), 82% removal was achieved with treatment costs between \$0.95 and \$4.93 USD/$m^3$, where the costs included electrical power, chemical, and electrode consumption [170].

The application can be extended to the shipping industry. When using electrocoagulation-floccuation in this industry, Drogui *et al.* was capable of removing 80% turbidity, 56% chemical oxygen demand (COD), 90% oil and grease, and 89% biochemical oxygen demand (BOD) having used bipolar electrode arrangements. The cost including energy and electrode consumption and sludge disposal ranged between \$1.54 to \$2.40 CAN/$m_3$ of ship waste effluent [171]. Khansorthong and Humson used electrocoagulation to treat wastewater from the pulp and paper mill industry using parallel iron electrode comparing current density, pH, and flow rate. When using the optimum conditions, it was found that to remove color (97%) and COD (77%) it would cost \$0.29 USD/$m^3$ of wastewater [172]. Orori *et al.* took sample a five locations from a Kraft pulp and paper mill effluent—primary settling tank, two aerated lagoons, a stabilization, and at the discharge comparing treatment efficiency using graphite electrodes and aluminum electrode with wood ash. Overall treatment with aluminum electrodes was better (60% BOD and 58.8% COD), but was more expensive than graphite (\$0.0006 to 0.0008 USD/$m^3$ of wastewater) *versus* (\$8.34 to \$31.74 USD/$m^3$ of wastewater) [173].

## 9. Conclusion

Electrocoagulation is a treatment process that is capable of being an effective treatment process as conventional methods such as chemical coagulation. Having observed trends over the last three years, it has been noted that electrocoagulation is capable of having high removal efficiencies of color, chemical oxygen demand (COD), biochemical oxygen demand (BOD), and achieving a more efficient treatment processes quicker than traditional coagulation and inexpensive than other methods of treatment such as ultraviolet (UV) and ozone. Unlike biological treatment which requires specific conditions, therefore limiting the ability to treat many wastewaters with high toxicity, xenobiotic compounds, and pH, eletrocoagulation can be used to treat multifaceted wastewaters, including industrial, agricultural, and domestic. Continual research using this technology will not only improve its efficiency, but new modeling techniques can be used to predict many factors and develop equations that will predict the effectiveness of treatment.

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