Review Article

Electrocoagulation in Wastewater Treatment: A Comprehensive Review of Heavy Metal and Pollutant Removal

ABSTRACT

Population explosion, urbanization, and industrialization have resulted in the generation of many types of wastewater. One of the most crucial aspects of water treatment is the elimination of pollutants/contaminants from wastewaters, as numerous industries cause environmental pollution. Rising scarcity of fresh water quality and quantity is a global concern. Discharging untreated wastewater into water bodies causes bad odour, nuisance and adverse impacts on human health, ecosystem and the world economy. Electrocoagulation is gaining ground as a potential electrochemical technique to treat wastewater due to its versatility, environmental compatibility and several other advantages. It is evident from the thorough literature review that electrocoagulation is the most frequently used and proficient process for the treatment of wastewaters containing pollutants/contaminants. During electrocoagulation in the electrochemical reactor, sacrificial anodes dissolute to release active coagulant flocs into the water/wastewater. During electrolytic reactions hydrogen gas evolves at the cathode. Many treatment methods, including adsorption, membrane filtration, coagulation/flocculation, and ion-exchange, advanced oxidation process, Moving Bed Bio-reactor, Sequencing Batch Reactor, Upflow Anaerobic Sludge Blanket, Trickling Filter, Rotating Biological Contactors are used to remove pollutants/contaminants from water/wastewater. These aforementioned methods are capital intensive, require large areas, chemicals, and a high level of instrumentation and generate secondary sludge, which poses a risk to the environment without proper disposal. To overcome these drawbacks, Electrocoagulation to treat water/wastewater can be considered. This review article focuses on understanding the role of electrochemical coagulation technique in treating wastewater and the effects of different system characteristics and operating parameters. The first few sections of this article help readers quickly understand the adverse impacts of untreated wastewater and the importance of electrochemical coagulation in water/wastewater treatment. The later sections discuss the chemical reactions, mechanisms, and effects of different operating parameters in the electrochemical reactor, which contribute to the potential removal of pollutants/contaminants from water/wastewater. It also includes a section snippet about microplastics removal and three dimensional electrocoagulation technique which is the latest and attention gaining technique in wastewater treatment. This article includes facts and findings considered from the published research and/or review articles.

Keywords: Electrocoagulation, Wastewater, Coagulant, Heavy metals

Introduction

Urbanization is producing an increasing amount of wastewater in conjunction with population growth, economic development, and a high standard of living (Drechsel *et al.*, 2015). Several industries have a significant environmental impact as they use resources like water and electricity and produce waste and wastewater. Most cities in developing countries generate around 30-70 mm^3 of wastewater per capita per year (Edokpayi et al., 2017). Central Public Health & Environmental Engineering Organisation (CPHEEO) estimated that about 70-80% of total water supplied for domestic use gets generated as wastewater (Kaur et al., 2012).

Industrial effluents or other wastewaters are characterized by high turbidity, conductivity, chemical oxygen demand (COD), biological oxygen demand (BOD), total suspended solids (TSS), total dissolved solids (TDS), chlorides, nitrates, phosphates and other parameters (Kanu et al., 2011; Ma et al., 2020; Akan et al., 2010; Aniyikaiye et al., 2019). Proper wastewater management can reduce pollution and augment clean water supply, simultaneously promoting sustainable development and a circular economy (Jones et al., 2021).

Environmental issues of untreated wastewater

The raw (untreated) wastewater has detrimental effects on the environment, agriculture, and contributes to innumerable waterborne outbreaks. An individual can be exposed to the chemicals present in wastewater by ingestion or inhalation (Okereke et al., 2016). Several major microbes present in untreated sewage are *T. coli*, *F. coli*, *Streptococcus*, *Salmonella*, *Firmicutes*, *Bacteroidetes*, *Actinobacteria*, and *Proteobacteria* (Singh *et al.*, 2004; Shanks et al., 2013). Municipal wastewater contains a conglomeration of human enteric microbiota (*Salmonella*), which can induce gastrointestinal illnesses (Yan et al., 2018).

In 2016, 37.7 million Indians were affected by waterborne diseases annually (Praveen et al., 2016). Leakage of sewer lines into drinking water and its consumption cause waterborne illnesses like fever, fatigue, nausea, diarrhoea, weight loss, abdominal pain, parasitic infection, etc (Praveen et al., 2016; Cissé, 2019). Wastewater effluents contain anthropogenic compounds that can damage the endocrine system (Akpor & Muchie, 2011). Toxic metals in the industrial effluents like nickel (Ni), cadmium (Cd), lead (Pb), cobalt (Co), copper (Cu), and mercury (Hg) can cause organ and nervous system damage, cancer, and death (Karri et al., 2021).

Heavy Metals	Health Hazards
Arsenic	Carcinogenic, producing liver tumors, skin and gastrointestinal effects
Mercury	Corrosive to skin, eyes and muscle membrane, dermatitis, anorexia, kidney damage and severe muscle pain
Cadmium	Carcinogenic, cause lung fibrosis, dyspnea and weight loss
Lead	Suspected carcinogen, loss of appetite, anemia, muscle and joint pains, diminishing IQ, cause sterility, kidney problem and high blood pressure
Chromium	Suspected human Carcinogen, producing lung tumors, allergic dermatitis
Nickel	Causes chronic bronchitis, reduced lung function, cancer of lungs and nasal sinus
Zinc	Causes short-term illness called “metal fume fever” and restlessness
Copper	Long term exposure causes irritation of nose, mouth, eyes, headache, stomachache, dizziness, diarrhea
Iron	Leads to organ damage, particularly in the liver, heart, and pancreas, and can cause conditions like hemochromatosis, liver cirrhosis, and diabetes. Additionally, it can generate oxidative stress, increasing the risk of diseases such as cancer and neurodegenerative disorders

Manganese	Leads to neurological problems, such as manganism, which resembles Parkinson's disease with symptoms including tremors, muscle rigidity, and behavioral changes. Chronic exposure can also cause respiratory issues, including lung inflammation and impaired lung function

Table. 1 Effects of heavy metal on health (Orisakwe et al., 2012)

Large amounts of nutrients (phosphorous and nitrogen) in municipal wastewater accelerate the intensity of eutrophication, which in turn causes algal bloom, reduced level of dissolved oxygen (DO), increased mortality of fish, increased incidences of toxic phytoplankton and destabilized aquatic ecosystem (Preisner et al., 2020; Preisner et al., 2021; Suryawan et al., 2021; Igbinosa & Okoh, 2009; Carey & Migliaccio, 2009).

Different wastewater treatment methods

The treatment and disposal of wastewater is an important environmental consideration as the majority of wastewater is a form of industrial pollution. Various treatment methods are being practiced to treat wastewater with high BOD and COD concentrations, these include chemical methods (precipitation, coagulation-flocculation and ion exchange) and biological treatment methods (Upflow Anaerobic Sludge Blanket, Activated Sludge Process, Sequencing Batch Reactor, Trickling Filter and Moving Bed Bio Reactor) which have been promulgated as the removal or recovery of the pollutants from the waste streams with varying degrees of success. These processes have some drawbacks such as they require higher HRT (Hydraulic Retention Time) for solids to settle and generate large amounts of sludge which requires further treatment along with proper disposal methods. Anaerobic digestion is considered as an environmentally sound biological treatment process. This process has many advantages over other treatment methods like it minimizes the use of large areas of land, avoids nuisance, bad odour and reduces organic load and pathogens, while methane and organic fertilizers are obtained as final metabolic end products (Holm-Nielsen et al., 2009; Beyene et al., 2014). Nevertheless, establishing an anaerobic digester at a laboratory scale poses challenges.

Advanced Oxidation processes include treatment with hydrogen peroxide, UV, ozonation, photocatalysis, wet air oxidation, ultrasound, Fenton, photo-Fenton and electrochemical oxidation (Swaminathan et al., 2013). Among these treatment methods, Electrochemical methods for water/wastewater treatment have been receiving greater interest in recent years. The following section provides more information about Electrochemical coagulation for treating wastewaters that offer distinctive advantages.

Effluents to be discharged on/to inland surface water, irrigation land, and public sewers should be within the permissible standards set by the State or Central Pollution Control Board (CPCB) as shown in Table 2.

Significance of Electrochemical coagulation (ECC)

Presently, there is a demand for new and environmentally friendly wastewater treatment technology as freshwater is polluting. Electrocoagulation is one technology developed to overcome the drawbacks of conventional wastewater treatment methods. It is a recognized environmentally friendly method for treating wastewater (Tegladza et al., 2021). Electrochemical treatment facilitates environmental protection by substantially reducing the polluting effects of wastes and deadly substances in the effluent. Electrolysis is a non-biological, chemical-free, and environmentally friendly process that provides better treated water quality. The electrocoagulation process's flexibility and setup allow the treatment of various wastewaters from industrial and household sources and help remove different contaminants/pollutants (Tahreen et al., 2020). Electrocoagulation (EC) is a purification system that employs micro-electrical currents to extract finely suspended particles from water or wastewater by destabilizing or neutralizing the repulsive forces that maintain the particles in suspension (Mao et al., 2023). It is a novel option capable of serving with low hydraulic retention time (HRT) for treating a variety of polluted/contaminated waters and wastewaters (Malinovic et al., 2018) with a built-in disinfection potential (Ghernaout et al., 2019; Ghernaout & Elboughdiri, 2020).

Electrocoagulation is a novel, more compact, versatile, promising, and robust treatment option than traditional wastewater treatment (Kabdaşlı et al., 2012). This process employs the theories of chemical coagulation and electrochemistry to treat and remove contaminants from water and wastewater (Ghernaout, 2020). Myriad studies have shown that electrocoagulation can be used in the defluoridation of surface water and groundwater (Kim et al., 2016; Mousazadeh et al., 2021; Castañeda et al., 2021; Das & Nandi, 2019), removal of dyes, heavy metals, inorganic ions, toxicants, recalcitrant organic compounds, colloidal matter, dissolved solids, pesticides, microplastics, radionuclides, harmful microorganisms and pollutants/contaminants from wastewater (Shaker et al., 2023; Islam, 2019; Houssini et al., 2024; Sahu et al., 2014). It is widely used to treat landfill leachate, tar sand and oil shale wastewater, saline wastewater, chemical mechanical polishing wastewater (Can et al., 2006; Niam et al., 2007), slaughterhouse or abattoir wastewater (Ngobeni et al., 2022; Bayar et al., 2011; Nwabanne & Obi, 2017), tannery wastewater (Feng et al., 2007; Babu et al., 2007; Apaydin et al., 2009), textile wastewater (Demirci et al., 2015; Zaroual et al., 2006), pharmaceutical wastewater (Dindaş et al., 2020), hospital wastewater (Hassoune et al., 2024; Yánes et al., 2021), ayurvedic hospital wastewater (Mahesh et al., 2022), industrial wastewater (Babu et al., 2019), sugar processing industrial wastewater (Patel et al., 2022), potato chips manufacturing wastewater (Kobya et al., 2006), paint manufacturing wastewater (Akyol, 2012), can manufacturing wastewater (Kobya & Demirbas, 2015), chocolate manufacturing wastewater (García-Morales et al., 2018), winery wastewater (Kara et al., 2013), baker's yeast wastewater (Kobya & Delipinar, 2008), cheese whey wastewater (Un et al., 2014), distillery spent wash (Khandegar & Saroh, 2014), soft drink industrial wastewater (Julaika et al., 2019), marigold flower processing industrial wastewater (Damaraju et al., 2020), coking wastewater (Choudhary et al., 2017), cork boiling wastewater (Silva et al., 2022), metal plating wastewater (Akbal & Camcı, 2012), pulp and paper mill wastewater (Camcioglu et al., 2017), coffee pulping/processing wastewater (Gururaj & Kumar, 2021; Phan et al., 2019), olive mill wastewater (Yassine et al., 2018; Inan et al., 2004), refectory oily wastewater (Xu & Zhu, 2004), dairy wastewater (Chezeau et al., 2020), mine wastewater (Shahedi et al., 2023), jewelry industry wastewater (Pratiwi et al., 2021), etc. Many studies have shown the application of Electrocoagulation technique in the treatment of wastewater containing heavy metals such as mercury (Hg), arsenic (As), iron (Fe), zinc (Zn), copper (Cu), nickel (Ni), lead (Pb), manganese (Mn) and cadmium (Cd) (Prasetyaningrum et al., 2021; Oluwabusuyi, 2021; Hawass & AlJaberi, 2022; AlJaberi & Hawaas, 2023; Yu et al., 2023; Bakry et al., 2024; Shaker et al., 2023; Salim et al., 2024).

Microplastics removal by electrocoagulation

Microplastics (plastic particles sized between 100 nm and 5 mm) are pervasive contaminants, nearly prevalent in all environmental compartments (Prata et al., 2019). Nowadays, it is a major concern in the scientific community because of its harmful effects on living beings (Ricardo et al., 2021). Microplastics enter aquatic environments via many paths, such as household wastewater, sewage effluent, runoff from plastic production facilities, and the disintegration of bigger plastic materials (Esskifati et al., 2024). Unfortunately, present wastewater treatment plants are not well equipped to eliminate microplastics. As a result, these particles will escape treatment facilities, find their way into surrounding water bodies, and accumulate over time (Carr et al., 2016). Microplastics can cause health implications, particularly for women, which affect genetics, brain development, and respiratory rates (Jain et al., 2021). A study by Subair et al., 2024 investigated the influence of various combinations of aluminum (Al) and stainless steel (SS) electrodes to remove polystyrene microplastics from water, such as Al-Al, SS-SS, Al-SS, and SS-Al. Among these combinations, it was discovered that the Al-Al pairing displayed excellent efficiency in microplastic removal with a simultaneous decrease in energy consumption. An interpenetrating bipolar plate electrocoagulation reactor was used to remove mixed pollutants of microplastics and heavy metals from the secondary effluent of a wastewater treatment plant. At a current density of 12 mA/cm2, an initial pH of 6, and a reaction duration of 20 minutes, heavy metals and microplastics were removed at rates of 95.16% and 97.5%, respectively (Xu et al., 2022). The most effective removal of organics and microplastics from laundry wastewater was achieved at 2.16 A current, pH 9, and a 60-minute reaction period using the Fe-Al electrode combination. COD, surfactant, color, and microplastic were removed with efficiencies of 91%, 94%, 100%, and 98%, respectively (Akarsu & Deniz, 2021).

Three-dimensional electrocoagulation

Three-dimensional (3D) electrode-based electrochemical techniques have gained a lot of attention in recent times. In comparison to two-dimensional (2D) electrochemical processes, the introduction of particle electrodes results in a higher specific surface area and shorter distance of mass transfer, making it more effective and promising for environmental applications (Zhang et al., 2013). The third electrode in 3D electrochemical methods can be a particle electrode or bed electrode placed between the anode and the cathode. Materials like powdered or granular activated carbon, metal particles, metal oxides, metal foams, carbon aerogel, kaolin, zeolite, ceramics, and steel slag particles, have been used as particle electrodes, as they exhibit significant adsorption and electrosorption, high catalytic activity, and a large surface area for electrochemical oxidation and helps in pollution reduction (Ma et al., 2021). 3D-ECC was used to treat healthcare facility wastewater and clearwater reclamation of 85–90% with maximum pollutants/contaminants removal within a short hydraulic retention time (HRT) of 75 minutes was reported by Singh et al., 2019. Metal-impregnated granular activated carbon (MIGAC) was employed as a third particle electrode in treating refinery wastewater with aluminum and stainless steel disk electrodes, which resulted in the effective removal of turbidity and COD (Theydan & Mohammed, 2022; Theydan et al., 2024). Waste aluminum scraps were used in three-dimensional electrochemical technology to treat landfill leachate nanofiltration concentrate. In the two-dimensional electrochemical technology (2DET), Ti/RuO2 and graphite were used as anodes. The removal efficiencies of color, COD, and TOC were 98.94 %, 51.93 %, and 67.46 %, respectively using Al 3DET at 120 minutes. It was followed by Fe EC post treatment as it provided good neutralization and enhanced the effects for Al 3DET (Li et al., 2024).

Pros and cons of electrocoagulation

In recent years, electrocoagulation has gained popularity as it combines the performance and advantages of conventional coagulation, flotation, and conventional electrochemical treatment of water and wastewater (Kuokkanen et al., 2013). It does not require external chemicals for pollution treatment and eliminates the need to transport, handle, or store chemicals, which generates additional benefits of cost savings. Also, it prevents the production of unwanted by-products (Gururaj & Kumar, 2021; Senathirajah et al., 2023). Trivalent chemical coagulants, such as Alum (aluminum (Al) salts) or $FeSO_4$ (iron (Fe) salts), are often employed in coagulation and flocculation to neutralize particles and promote floc formation. In electrocoagulation, the necessary metal ions are supplied by the metal plates that constitute the electrodes (Perren et al., 2018). The advantages of electrochemical methods over traditional treatment methods are cost-effective, simple equipment that is flexible to operate and automate, safe, environmentally compatible, energy efficient, excellent settling, good filterability, short retention time, and produces low amount of sludge, and neutralize the pH of the solution during electrolysis (Damaraju et al., 2019; Sahana et al., 2018; Barrera-Díaz et al., 2011; Nidheesh et al., 2022). The hydrophobicity of the produced sludge reduces the need for dewatering (Lu et al., 2021; Shen et al., 2022; Tang et al., 2022). Compared to traditional chemical coagulation, electrocoagulation offers wastewater with low salinity and acidity, improved coagulant dispersion, and intrinsic electroflotation separation capabilities (Gadd et al., 2010). Furthermore, the hydroxyl radicals produced by water oxidation form hydrogen peroxide, which can convert harmful species into non-toxic species (Lu et al., 2021). Recent developments in technology have enabled electrocoagulation to operate at lower currents (Javed & Mushtaq, 2023).

Some of the drawbacks of electrocoagulation are the need to replace the sacrificial anodes after exhaustion, the passivation of electrodes due to oxide film, and the need for conductive aqueous media (Tsouris et al., 2001). Designing EC for drinking water requires a high electrode surface area to prevent ohmic voltage loss, as salt addition is not a viable option (Dubrawski & Mohseni, 2013).

Table 2. General standards for discharge of effluents prescribed by Karnataka state Pollution Control Board (KSPCB)

Parameters	**Inland surface water**	**Public sewers**	**Land for irrigation**
Color and Odor	Practicable	-	Practicable
Suspended Solids (mg/L)	100	600	200
pH	5.5 – 9.0	5.5 – 9.0	5.5 – 9.0
Temperature	Shall not exceed 5°C above receiving water temperature	-	Shall not exceed 5°C above receiving water temperature
Oil and Grease (mg/L), Max.	10	20	10
Ammonical Nitrogen (as N), (mg/L), Max.	50	50	-
Total Kjeldahl Nitrogen (as NH_3), (mg/L), Max.	100	-	-
Free Ammonia (as NH_3), (mg/L), Max.	5.0	-	-
BOD (5 days at 20°C), (mg/L), Max.	30	350	100
COD (mg/L), Max.	250	-	-
Hexavalent Chromium (as Cr^{+6}), (mg/L), Max.	0.1	2.0	-
Copper (as Cu), (mg/L), Max.	3.0	3.0	-
Nickel (as Ni), (mg/L), Max.	3.0	3.0	-
Phenolic Compounds (as C_6H_5OH), (mg/L)	1.0	5.0	-
Iron (as Fe), (mg/L), Max.	3.0	3.0	-

Dissolved Solids (Inorganic), (mg/L), Max.	2100	2100	2100
Sulphate (as SO_4), (mg/L), Max.	1000	1000	1000

(**Source:** https://kspcb.karnataka.gov.in/industry-specific-standards)

Principle:

Electrocoagulation is a very simple and productive method for wastewater treatment. The EC process involves many chemical and physical mechanisms. Generally, aluminum or iron is dissolved by anodic dissolution. A range of coagulant species and hydroxides are formed which destabilize and coagulate the suspended particles or precipitate and adsorb dissolved contaminants (Paul, 1996). It is generally accepted that the EC process involves three successive stages (Mollah et al., 2004).

(i) Formation of coagulants by electrolytic oxidation of the electrode

The main reaction occurring at the metal anode is dissolution:

$$M(s) \quad M(aq)^{n+} + ne^-$$

Additionally, water electrolysis occurs at the cathode and anode:

$2H_2O(l) + 2e^- \quad H_2(g) + 2OH^-$ (cathodic reaction)

$2H_2O(l) + \ 4H^+(aq) + \ O_2(g) + 4e^-$ (anodic reaction)

(ii) Destabilization of the contaminants, particulate suspension, and breaking of emulsions.

A direct electrochemical reduction of metal cations (Mn+) may occur at the cathode surface:

$M^{n+} + ne^- \quad nM^0$

Furthermore, the hydroxide ions formed at the cathode increase the pH of the wastewater thereby inducing precipitation of metal ions as corresponding hydroxides and co-precipitation with hydroxides:

$$M^{n+} + n\ OH^- \quad M(OH)_n(s)$$

iii) Aggregation of the destabilized phases to form flocs. Anodic metal ions and hydroxide ions generated at the electrode surfaces react in the bulk wastewater to form various hydroxides and built up polymers.

Experimental set up:

Water/wastewater passes through the gaps between the plate electrodes in an EC system, which is commonly built of them (Chen, 2004*)*. The electrode configuration of the EC system can be done in a number of ways. The direction of flow between the electrodes might be either vertical or horizontal. Bipolar and monopolar electrodes are both possible. Every anode and every cathode in the monopolar systems (Fig.1) is connected to every other electrode. The bipolar systems depicted in Figure 1(a) include connecting the outermost electrodes to a power source, which allows current to flow through and polarize the other electrodes. The electrode's side facing the anode in a bipolar system is negatively polarized, and the opposite is true for the electrode facing the cathode. The best performance was obtained using mild steel electrodes in bipolar configuration.

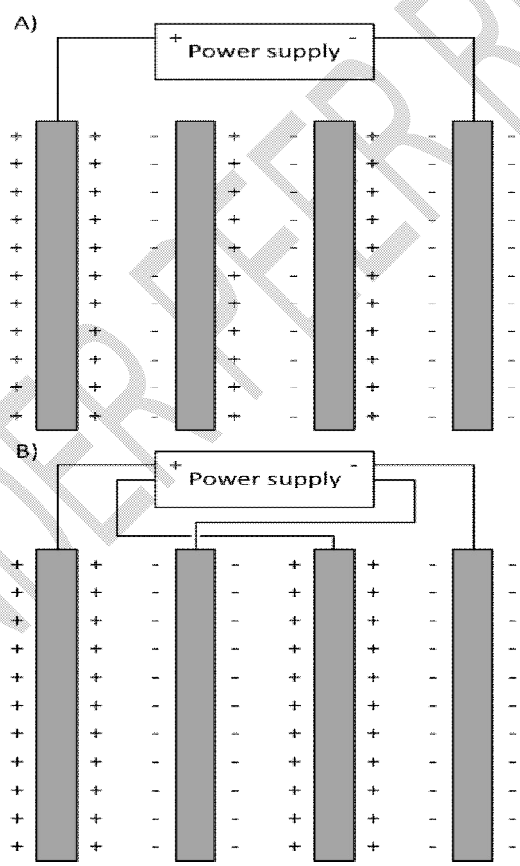

Fig 1**:** Connections and electrode polarity in a) bipolar and b) monopolar EC systems (Vepsäläinen et al., 2007)

In monopolar arrangement, two type of connection are used monopolar parallel arrangement, in this arrangement power supply is connected to each electrode in manner of anode-cathode-anode-cathode; second type is monopolar series arrangement, in this type of arrangement first and last electrode are connected with power supply and rest of others are inter connected to each other. Whereas, in bipolar parallel arrangement power supply is connected to first and last electrode rest of the electrode is sacrificial electrode and there is no inter connection between them (Mollah, *et al*, 2001).

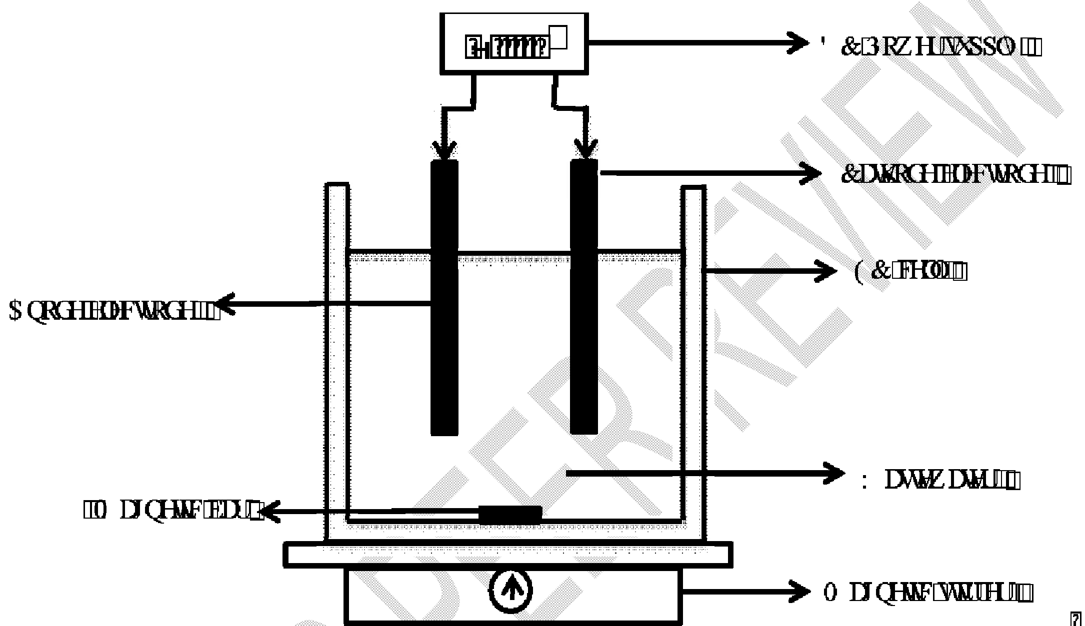

Fig 2. Systematic diagram of electrocoagulation process (Mollah et al., 2001)

Effect of different operating parameters

Electrode Materials

Electrocoagulation (EC) is an advanced water treatment technology that leverages electrical currents to remove contaminants from wastewater. By applying a direct current to electrodes submerged in the wastewater, EC induces the dissolution of electrode materials and the formation of coagulants. These coagulants, in turn, aggregate suspended particles and pollutants, facilitating their removal through subsequent separation processes. The efficiency and effectiveness of EC are highly dependent on the choice of electrode materials, which can significantly influence the coagulation process and overall treatment performance (Chen et al., 2017; Kim et al., 2020).

The selection of electrode materials is crucial because it affects not only the rate of contaminant removal but also the operational stability and cost of the system. Commonly used electrode materials include aluminum, iron, stainless steel, and titanium, each offering unique advantages and challenges. Understanding the interactions between these materials and the wastewater matrix is essential for optimizing EC systems for various industrial and municipal applications (Li et al., 2018; Pelegrini et al., 2020).

1. Aluminum Electrodes: Aluminum electrodes are among the most frequently used in electrocoagulation due to their cost-effectiveness and efficiency. When an aluminum electrode is used, it undergoes oxidation and dissolution to form aluminum hydroxide, which acts as a coagulant. The relevant chemical reaction can be expressed as follows:

$$2Al(s) + 6H_2O(l) \rightarrow 2Al\,(OH)_3\,(s) + 3H_2(g)$$

Here, aluminum reacts with water to produce aluminum hydroxide and hydrogen gas (Tzoupanos et al., 2019). This reaction is beneficial because aluminum hydroxide is highly effective at binding with pollutants, facilitating their removal from wastewater (Pelegrini et al., 2020).

2. Iron Electrodes: Iron electrodes are another popular choice in EC systems. Iron, when used as an electrode material, undergoes oxidation to form iron ions, which subsequently hydrolyze to form iron hydroxides. The reactions involved are:

$$Fe(s) \rightarrow Fe^{2+}\,(aq) + 2^{e^{-}}$$

$$Fe^{2+}\,(aq) + 2H_2O(l) \rightarrow Fe\,(OH)_2\,(s) + 2H^{+}\,(aq)$$

$$Fe^{2+}\,(aq) + O_2(g) + 2H_2O(l) \rightarrow Fe\,(OH)_3\,(s)$$

Iron hydroxides, particularly ferric hydroxide, are effective coagulants that help in aggregating and removing contaminants from water (Chen et al., 2017). This material is advantageous due to its relatively low cost and high coagulation efficiency.

3. Stainless Steel Electrodes: Stainless steel electrodes are increasingly used due to their durability and resistance to corrosion. These electrodes primarily consist of iron mixed with chromium and nickel, which helps prevent rusting and extends the lifespan of the electrodes. The main reactions occurring with stainless steel involve the oxidation of iron components:

$Fe(s) \rightarrow Fe^{3+}(aq) + 3e^{-}$

Stainless steel can generate iron-based coagulants similar to those from pure iron electrodes but with added resistance to oxidative wear (Li *et al*., 2018). This feature makes them suitable for long-term applications.

4. Titanium Electrodes: Titanium electrodes are notable for their stability and resistance to chemical attacks. They are often used as substrate materials for other coatings that enhance their electrocoagulation efficiency. Titanium itself does not directly participate in the coagulation process but supports other materials through stable electrode behavior:

Ti(s) remains largely inert during electrocoagulation

In practice, titanium electrodes are coated with conductive materials such as ruthenium or iridium oxides to enhance performance. These coatings contribute to the electrode's efficiency by improving its conductivity and durability (Kim *et al.*, 2020).

5. Composite and Coated Electrodes: In recent years, researchers have explored composite and coated electrodes to improve the performance of EC systems. These electrodes often combine materials like graphite, conductive polymers, or metal oxides to enhance conductivity and corrosion resistance. For example, graphite-based electrodes offer high conductivity and stability, while metal oxides can enhance the generation of coagulant ions (Zhao et al., 2020; Singh et al., 2022).

Electrolysis Time

Electrolysis time, or the duration for which an electric current is applied during electrocoagulation (EC), plays a crucial role in determining the effectiveness of the treatment process. The length of electrolysis impacts the amount of coagulant generated, the extent of pollutant removal, and the overall efficiency of the system. The relationship between electrolysis time and treatment performance involves several key factors and reactions, which are essential for optimizing EC processes.

The primary function of electrolysis in EC is to facilitate the dissolution of electrode materials, which leads to the formation of coagulants. For example, when aluminum electrodes are used, the electrolysis process results in the oxidation of aluminum, producing aluminum ions and hydroxides. The reaction can be summarized as:

$2Al\ (s) + 6H_2O\ (l) \rightarrow 2Al\ (OH)_3\ (s) + 3H_2\ (g)$

Longer electrolysis times generally result in the generation of more aluminum hydroxide, which enhances the coagulation process (Pelegrini *et al*., 2020). However, excessively long durations can lead to diminishing returns, where additional coagulant does not significantly improve pollutant removal but may increase energy consumption (Tzoupanos *et al*., 2019).

The effectiveness of electrocoagulation is also closely related to the duration of electrolysis. As electrolysis time increases, the concentration of generated coagulants rises, which typically improves the removal of suspended solids and contaminants. This relationship is evident in studies where increased electrolysis times led to higher removal rates of pollutants such as heavy metals and organic matter (Chen et al., 2017).

For instance, in a study by Li et al. (2018), it was observed that extending the electrolysis time enhanced the removal efficiency of pollutants from wastewater. However, the benefit is subject to a point of saturation, beyond which additional time provides marginal gains and could even lead to adverse effects such as excessive sludge formation (Kim et al., 2020).

Optimizing electrolysis time involves balancing between adequate coagulant generation and operational costs. Research indicates that there is an optimal range for electrolysis time, where the treatment efficiency is maximized without incurring unnecessary energy and maintenance costs. For example, an optimization study found that the best results were achieved with electrolysis times of around 30 to 60 minutes, beyond which the incremental benefits diminished (Chen et al., 2017).

Electrode Distance

Electrode distance, also known as inter-electrode distance, is a key parameter in electrocoagulation (EC) systems. It represents the gap between the electrodes through which the electric current passes. The distance between electrodes plays a crucial role in determining the efficiency of the electrocoagulation process, influencing factors such as current distribution, energy consumption, and overall treatment performance.

The distance between electrodes affects how evenly the electrical current is distributed across the electrodes. Generally, a smaller electrode distance results in a more uniform distribution of current, which enhances the coagulation process. This is because a reduced gap allows the electric field to be more concentrated, leading to better interaction between the electrodes and the wastewater (Gong et al., 2016). As a result, the dissolution of electrode material and the generation of coagulants become more efficient, improving the overall treatment effectiveness.

Energy consumption is another critical factor impacted by electrode distance. When electrodes are placed closer together, the electrical resistance of the solution is lower, which means that less energy is required to maintain the same current. On the other hand, increasing the electrode distance raises the solution's resistance, leading to higher energy consumption to achieve the same current flow. This increase in energy requirements can raise operational costs and affect the overall feasibility of the EC process. Therefore, optimizing the electrode distance is essential for balancing energy efficiency with treatment effectiveness (Huang et al., 2019).

The efficiency of coagulation is directly related to the electrode distance. A shorter distance typically results in higher coagulation efficiency because the coagulant generated from the electrode dissolution has less distance to travel to reach the contaminants. This can enhance the rate at which pollutants are aggregated and removed from the wastewater. However, an excessively short distance can lead to problems such as increased electrical short-circuiting and reduced operational stability. Hence, careful management is required to avoid such issues while maximizing coagulation efficiency (Zhang et al., 2020).

The reactions at the electrodes during electrocoagulation are influenced by electrode distance. For instance, with a small electrode distance, the following reactions are more favorable:

$M(s) \rightarrow Mn + (aq) + ne^{-}$

Here, M represents the electrode material, such as aluminum or iron, which dissolves into the solution as metal ions. These ions then react with water to form hydroxides:

$M^{n+}(aq) + nH_2O(l) \rightarrow M(OH)_n(s) + nH^+(aq)$

When the electrode distance is optimized, these reactions occur more efficiently, leading to improved coagulation performance (Deng & Zhao, 2015).

Electrical Conductivity

Electrical conductivity plays a crucial role in the electrocoagulation (EC) process, as it directly affects the efficiency of contaminant removal from wastewater. Conductivity refers to the ability of a solution to conduct an electric current, which is essential for the EC process where electrical current is used to induce coagulation reactions.

In EC, the electrical conductivity of the wastewater determines how easily an electric current can pass through the solution. Higher conductivity generally leads to more efficient current flow and enhanced coagulation performance. This is because increased conductivity reduces the electrical resistance of the solution, allowing for better distribution of current between the electrodes (Chen et al., 2017). When the wastewater has high conductivity, the rate of formation of coagulant agents, such as aluminum hydroxide or iron hydroxide, increases, leading to more effective removal of pollutants (Pelegrini et al., 2020).

Electrical conductivity affects the coagulation process by influencing the formation of coagulant flocs and their subsequent aggregation. In practice, wastewater with low conductivity requires additional chemicals or adjustments to increase its conductivity to achieve optimal coagulation. For example, adding salts like sodium chloride can enhance conductivity and improve the efficiency of the EC process (Li et al., 2018). Conversely, very high conductivity might lead to excessive ionization and increased electrode wear, which can reduce the system's lifespan and efficiency (Kim et al., 2020).

Monitoring and adjusting the conductivity of wastewater are essential for optimizing the EC process. Conductivity meters are used to measure the electrical conductivity of the solution, and this information helps in fine-tuning the treatment process. Adjustments may include altering the electrode configuration, adjusting the current density, or adding conductive salts to maintain optimal conductivity levels (Chen et al., 2017). Effective management of conductivity ensures that the electrocoagulation process remains efficient and cost-effective over time.

Temperature

Temperature plays a crucial role in the electrocoagulation (EC) process, influencing both the efficiency of pollutant removal and the overall operational stability of the system. Understanding how temperature affects electrocoagulation can help optimize treatment processes and improve performance.

Temperature directly impacts the reaction rates within electrocoagulation. As temperature increases, the kinetic energy of molecules also increases, leading to enhanced reaction rates. This is particularly relevant for the electrochemical reactions occurring at the electrodes. Higher temperatures can accelerate the dissolution of electrodes, such as aluminum or iron, resulting in a greater production of coagulants. For instance, an increase in temperature generally enhances the rate at which aluminum dissolves into aluminum ions and subsequently forms aluminum hydroxide, a key coagulant in the EC process (García-Gómez et al., 2017). This relationship between temperature and reaction kinetics is supported by the Arrhenius equation, which suggests that reaction rates increase exponentially with temperature.

The formation of coagulants is another aspect affected by temperature. In electrocoagulation, coagulants such as aluminum hydroxide or iron hydroxide are generated from the dissolution of electrodes. Higher temperatures tend to increase the solubility of gases and other substances, which can affect the stability and formation of these coagulants. For example, elevated temperatures can lead to a more rapid formation of iron hydroxides when using iron electrodes, improving the overall coagulation efficiency (Mollah et al., 2015). However, excessively high temperatures can lead to the formation of soluble complexes that may reduce the effectiveness of the coagulation process.

Temperature also affects the viscosity and electrical conductivity of the water being treated. As temperature increases, water viscosity decreases, which can enhance the movement of ions and the overall efficiency of the electrochemical reactions. Additionally, higher temperatures generally increase the electrical conductivity of water, improving the efficiency of the EC process by reducing electrical resistance (Santos et al., 2021). This improved conductivity allows for more efficient current distribution and better coagulation performance.

The temperature can influence the stability and longevity of electrode materials. Elevated temperatures can accelerate the wear and tear on electrodes, particularly those made from metals like aluminum and iron. Prolonged exposure to high temperatures can lead to increased corrosion rates and the degradation of electrode materials, which may necessitate more frequent replacements and maintenance (Liu et al., 2018). Therefore, managing the operating temperature is crucial to extend the lifespan of the electrodes and maintain the efficiency of the EC system.

Electrical conductivity

The conductivity of the solution is inversely related to resistance (Al-Rubaye et al., 2024). Conductivity generally comprises the effect of the electrical field applied as a consequence of the mobility of ions in the ambit (Öztürk et al., 2013). Nguyen et al., 2016 reported that the concentration of sodium chloride (NaCl) is directly proportional to the conductivity of the solution. Increased NaCl concentration of the solution leads to increased phosphate removal in a shorter electrolysis time. Ahmed et al., 2024 studied that raw textile wastewater and seawater had an electrical conductivity of 2033 μS/cm and 55200 μS/cm, respectively. They infused seawater with concentrations of 0%, 5%, 10%, and 15% to 600 cm^3 of raw textile wastewater. Increased seawater concentration and retention time increased the electrical conductivity, as seawater contains many minerals and salts. After 45 and 95 minutes of retention time, the lowest electrical conductivity was the same as the raw wastewater as there was no infusion of seawater. The highest conductivity after 45 and 90 minutes of retention time with 15% seawater addition was 9080 µS/cm and 9690 µS/cm respectively. The presence of cations and anions, like Mg^{2+} and Ca^{2+} in Seawater enhanced the removal of suspended solids, phosphate, color, and turbidity from wastewater. The spacing between electrodes directly correlates with the electrical conductivity. Increasing the interelectrode distance uses more power and improves removal efficiency (Gomes et al., 2007; Kim et al., 2002).

Current density

Current density is a crucial parameter in controlling the reaction rate in all the electrocoagulation processes. In batch electrocoagulation, only the operating current density can be directly regulated. It determines the coagulant dose and the bubble generation (Barrera-Díaz et al., 2011). As the current density increases, the efficiency of ion production in the electrodes also increases, which leads to increased floc production. During 30 minutes of the electrocoagulation process to treat sewage, the optimum current density was 1816 A/m^2, which resulted in 96% COD, 98.3% BOD, and 97.6% SS removal compared to 605 A/m^2 (Nasrullah et al., 2012). While treating poultry slaughterhouse wastewater, Bayar et al., 2011 noted that as the current density increased even the energy consumption increased. Irdemez et al., 2006 worked on the treatment of synthetic wastewater, where the phosphate removal rate and removal efficiency were increased by increasing the current density using Fe or Al electrodes. Researchers treated landfill leachate, and the results showed that a higher applied current improved the removal efficiency of pollutants because it made more metals and hydroxyls available to produce coagulants (Galvão et al., 2020). As the current density increased from 348 to 631 A/m^2 while treating leachate, the COD removal efficiency also increased from 18.3% to 27.3% in the first minute and from 45.5% to 59.1% at the end of 30 minute contact period (Ilhan et al., 2008).

pH

The electrochemical oxidation and reduction of water can change the pH on anode and cathode surfaces concerning the bulk pH (Barrera-Díaz et al., 2011). Initial pH is crucial for the electrochemical removal of heavy metals from simulated wastewater. The highest lead removal efficiency of 99% was obtained when the initial pH value was approximately equal to 9.5 and other parameters were fixed (Al-Jaberi & Mohammed, 2018). pH and chloride ions concentration can have a significant influence on the removal efficiency of hexavalent chromium because the reduction of Cr(VI) to Cr(III) by Fe^{2+} ions is preferred to occur in acidic conditions, but the coagulation of Fe^{3+} and Cr(III) is favourable in alkali conditions (Arroyo et al., 2009). In iron electrocoagulation reactors, the rate of Fe(II) oxidation at pH 5–7 is greatly reliant on the buffering capacity of the electrolyzed solution (Gendel & Lahav, 2010). In water, the chemical dissolution of aluminum is dependent on pH with higher rates observed at pH>12 (Mansouri et al., 2011). While treating the distillery spent wash or vinasse the initial pH was 4.4, 5.0, 7.0, and the solution pH increased from 4.4 to 7.3, 5.0 to 8.0, and 7.0 to 9.7, respectively at 3A current. The increase in pH was due to the accumulation of OH^- ions resulting from the reduction process of water (Syaichurrozi et al., 2020). When the initial pH of the influent was 7.2, there was the highest microplastics removal with the final removal rate of 93.2% for polyethylene, 91.7% for polymethylmethacrylate, 98.2% for cellulose acetate, and 98.4% for polypropylene, respectively (Shen et al., 2022).

Table 3 Research work on Electrochemical coagulation of different wastewater

Wastewater type	**Electrode used**	**Operating conditions**	**Focus parameter & initial value**	**% removal**	**Reference**
Chicken processing plant (CPP) wastewater	5 Fe	Type: continuous Volume= 2.5 L for horizontal and 3.75 L for vertical CEC	COD=1140 mg/L, BOD_5=570 mg/L, TSS=264 mg/L, Oil grease= 38	COD= 86%, BOD_5= 97%, TSS= 85%, oil grease=	Gomes et al., 2018

		Electrode dimension: a) horizontal- 10.8×10.5×0.3(cm) b) Vertical- 14×10×0.6 (cm) Electrode gap: 2.1 cm	mg/L, fecal coliform (FC)> 1000000 MPN/100 mL, NH_3N=2.7 mg/L	18%, Fecal Coliform= 85%, NH_3-N= 7.4%	
Coffee processing wastewater	2 Al	Type: batch Volume= 1 L Electrode size:7×7 (cm) Electrode gap: 1 cm	COD=8320 to 12840 mg/L (arabica), NH_3-N =34.1 mg/L, NO_3-N=28.2 mg/L, P=40.6 mg/L	COD= 93%, NH_3-N= 90.5%, NO_3-N= 91.4%, P= 94.3%	Asha & Kumar, 2015
Dairy wastewater	4 MS (Mild Steel)	Type: batch Electrode dimension: 10×5×0.2 (cm) Electrode gap: 2.5 cm	COD=18300 mg/L, oil & grease=4570 mg/L	COD= 98%, oil & grease= 99%	Sengil & Ozacar, 2006
Printing ink wastewater	2 Al & 2 Fe	Type: batch Electrode gap: 3 mm	COD=9500 ± 2500 mg/L, color: black	COD= 75% and color= 99% for both the electrodes	Papadopoulos et al., 2019
Wet-spun acrylic fibers manufacturing wastewater	2 Fe	Type: batch Electrolysis time (ET)= 100 min Volume= 2 L Electrode dimension: 14×5×0.2 cm Stirring speed:150 rpm	COD=248.2mg/L, TOC= 85.2 mg/L, pH= 7.16, BOD_5=5 mg/L	TOC= 44% at pH=5	Gong et al., 2014
Distillery wastewater	2 Al	Type: batch ET= 3 hours Volume=1.5 L Electrode size: 5×5 (cm)	COD=46440 mg/L, BOD/COD ratio=0.16	COD=72.3% BOD/COD ratio=0.68	Krishna et al., 2010

		Electrode gap: 2 cm			
Coffee processing industrial wastewater	4 SS, 4 Fe and their combination	Type: batch Volume= 1 L Surface area/Volume=20 m^2/m^3 Electrode gap: 10 mm Stirring speed: 350 rpm	COD=1984 mg/L, color=7000 PCU	COD= 87%, color=97.1%	Sahana et al., 2018
Rice grain based distillery effluent	4 Cu	Type-batch ET=1.9h Volume=1.4 L Electrode dimension: 8×7×0.2 (cm) Electrode gap: 2 cm	COD=11500 mg/dm^3, color=398 PCU	COD= 80%, color= 65% at pH 3.5, current density of 89.3 A/m^2 (optimal)	Prajapati et al., 2016
Coffee processing wastewater	2 Al & 2 Fe	Type: batch Volume= 1 L Electrode size:7×7 (cm) Electrode gap: 1 cm	COD=12840 mg/L	COD= 97% and 89% using Al and Fe electrodes respectively	Asha et al., 2016
Pulp and paper wastewater	Al	Type: batch Volume=500 mL Electrode dimension: 50×60×3 (mm) Electrode gap: 1 to 4 cm	COD=620 mg/L, BOD=210 mg/L, color=255 PCU	COD=90%, BOD= 87%, color= 94%	Sridhar et al., 2011
Textile wastewater	10 Fe	Type: batch Electrode dimension: 400×600×3 (mm) Electrode gap: 1.5 cm	pH=10.4, COD=705 mg/L	COD= 79.86% at neutral pH, than at pH of 5-6.	Hossain et al., 2013
Pulp and paper mill wastewater	CTAB-bent and (OH-Al-CTAB-	Type: batch Volume= 500 mL Electrode dimension: 40×10×120 (mm)	pH=7.83, COD=256 mg/L, EC=2200 μS/cm, TDS=1.86 g/L,	COD= 84.3%, color= 93% using OH-Al-	Chu et al., 2016

	bent)* with 2SS in a 3D electrode system	Electrode gap: 4 cm	color: brown	CTAB-bent	

* CTAB-bent: cetyl trimethyl ammonium bromide modified bentonite & OH-Al-CTAB-bent: hydroxy-aluminum pillared organic bentonite

Conclusion

This review comprehensively examines electrochemical coagulation as the most commonly employed method for removing pollutants/contaminants from wastewater effluents. Recent research articles have addressed the adoption of electrocoagulation in treating various wastewaters. This technique can be chosen due to its widespread use, allowing for a clarification of their current status and emphasising how different factors influence their effectiveness. Among the various methods to treat water/wastewater, EC has demonstrated high success in eliminating various pollutants/contaminants at different concentration levels in water/ wastewater. Additionally, EC is recognized as an inexpensive and environmentally friendly solution with numerous advantages. In some cases, it also helps in the reclamation of clear water. Therefore, it is essential to incorporate electrochemical coagulation into water or wastewater treatment facilities. However, further studies must be conducted on optimizing parameters, system design, and economic viability to expand the laboratory-scale systems to align with industrial demands.

Disclaimer (Artificial intelligence)

Option 1:

Authors hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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