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# A CRITICAL REVIEW OF ELECTRODE MATERIALS, REACTION MECHANISMS, AND REACTOR DESIGNS IN ELECTROCOAGULATION FOR WASTEWATER TREATMENT

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## ABSTRACT

### Aim of the study

Electrocoagulation (EC) is a well-established wastewater treatment technique that has been extensively investigated for a variety of wastewater contaminants. The aim of the paper is to review electrocoagulation (EC) as a wastewater treatment method.

### Methods and materials

The paper summarises and explains recent developments in reactor geometries and scale-up, electrode materials and modifications, reaction mechanisms and kinetics, and operating parameters (current density, pH, conductivity, inter-electrode distance, temperature). The review covers coupled, hybrid EC-based systems, providing comparative performance by wastewater type, and evaluates the techno-economic and environmental factors that influence field implementation.

### Results and conclusions

The key findings of the paper are: 1) iron- and aluminum-based electrodes remain dominant, but non-metallic and modified electrodes show promise for improved selectivity and reduced passivation; 2) the primary removal mechanisms are anodic electro-dissolution, followed by hydrolysis and adsorption/sweeping flocculation, and kinetic behavior varies by pollutant category and reactor operation mode; 3) reactor design (A/V ratio, electrode geometry, flow regime) exerts a pronounced influence on mass transfer, energy consumption, and scale-up potential; 4) practical limitations include passivation of electrodes, energy consumption, and sludge management. The review concludes with targeted research trajectories (anti-passivation material design, standard pilot-scale test procedures, lifecycle assessments, biological and membrane system integration approaches) and outline where future work will optimally fill knowledge gaps.

**Keywords:** electrocoagulation, wastewater treatment, electrodes, reactor design, reaction mechanism

## INTRODUCTION

Water scarcity is a major problem in the twenty-first century. Approximately 2 billion people worldwide lack access to affordable, clean, and safe drinking water, leading to an average of 7.8 million annual deaths due to insufficient water hygiene and sanitation. Furthermore, drought impacts nearly 55 million individuals each year, resulting in over 5 billion USD in economic losses. Since 1980, yearly water use has

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risen by 1%, a trend anticipated to persist until 2050 (Naje et al., 2016). The demand for reusable water cuts across multiple sectors, including industrial, agricultural, and residential domains. Water scarcity may be less of an issue if wastewater is treated. The conventional wastewater treatment process consists of three main stages: primary treatment, secondary treatment, and tertiary treatment. Primary treatment involves a bar screening and a sedimentation basin to remove suspended solids from the wastewater. Secondary treatment applies biological methods, including the biological filter process and the activated sludge process, to break down complex organic compounds into non-toxic substances.

Tertiary treatment techniques include chlorination processes, ultraviolet disinfection techniques, and membrane bioreactors that are applied during extensive water treatment (Kuokkanen et al., 2013). The entire water treatment process can be categorised as either a separation procedure or a degradation method. The separation process involves converting contaminants present in water from one state to another, typically to a solid state. The best example of this process can be found in the adsorption mechanism. The degradation process, which is mostly used to remove these contaminants, might end up breaking them down until complete mineralisation is achieved (Shahedi et al., 2020). Conventional wastewater treatment involves biological, physical-chemical, adsorption, and membrane filtration techniques. Biological treatments require tightly controlled conditions, long retention times, and large space, and they produce unwanted byproducts. Chemical methods consume significant quantities of chemicals, raising the costs and risks of secondary contamination. Membrane and adsorption filtration alone are inadequate for heavily polluted wastewater without extensive pre-treatment. Furthermore, adsorption efficiency is affected by solution pH, requires long processing times, and declines with repeated use, limiting its effectiveness in wastewater treatment (Bharath et al., 2018).

Additionally, membrane filtration fails over time due to reduced flow rate caused by impurities clogging the pores (Padmaja et al., 2020). Therefore, current research on wastewater treatment mainly focuses on electrochemical processes (Nidheesh and Singh, 2017). Electrocoagulation (EC) is a rapidly developing electrochemical technology that has shown great promise and wide applicability in wastewater treatment over the past three decades (Ugrina and Milojkovic, 2024; Mao et al., 2023). Figure 1 shows a schematic diagram of an electrocoagulation tank. Electrocoagulation utilises the anodic dissolution of a sacrificial metal electrode (usually aluminium or iron) to generate flocculants in situ. These flocculants then hydrolyse to form amorphous hydroxides, which can remove various pollutants through adsorption, charge neutralisation, and flocculation (Syam Babu et al., 2020; Issaka, 2024). Electrocoagulation (Ec) has been extensively studied for the use in treating various types of wastewater, including that from textile dyeing, petrochemical and oil industries, heavy metal contaminated water, and municipal and agricultural waste. This is due to its ease of operation, low chemical reagent usage, and applicability to all wastewater sources (Wang et al., 2025; Zhang et al., 2024). Further research is needed to fully understand the electrocoagulation process. A study was conducted wherein experiments allowed to learn how various operating parameters, such as current density, pH, conductivity and electrode spacing or hydraulic conditions, might influence pollutant removal efficiency (Rahman et al., 2024; Dindas et al., 2020). Such studies tend to report a wide range of performance indicators and use different kinds of reactors. They also lack data on key performance parameters such as mass loss at the electrode material in water treatment systems as compared to

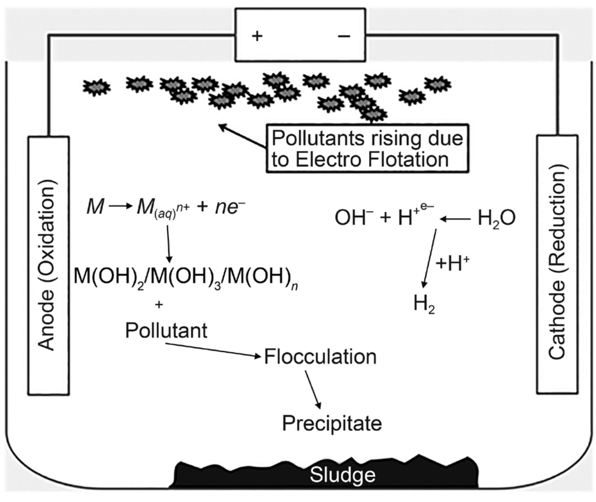


**Fig. 1.** Schematic of the electrocoagulation cell (Source: Syam Babu et al., 2020; Issaka, 2024)

energy consumption or sludge formations (Nidheesh, Khan et al., 2022; Weerasinghe et al., 2025).

Hence, cross-comparison of work is difficult, which hinders the development of design and operating guidelines universally applicable. Also, while several reviews have generalized EC fundamentals or applications to specific types of wastewater (Sayin et al., 2024; Hu et al., 2023), few have provided a comprehensive, critical survey of electrode materials, reaction mechanisms, and reactor configurations, including both scientific developments and practical issues such as cost, scaling, and environmental concerns (Nemade et al., 2021; Bashir, 2023). Due to its adaptability, ease of operation and the capability to handle a variety of pollutants, electrocoagulation (EC) is considered an efficient wastewater treatment method and water purification technique (Taylor et al., 2014). Compared with chemical flocculation, electrocoagulation is a viable method of wastewater treatment because it offers both high purification performance with no additional chemicals required. In contrast, since electrocoagulation does not employ chemical flocculants, it causes no secondary pollution. Moreover, the bubbles generated during electrocoagulation encourage pollutants to rise to the surface (Kim et al., 2020; Ingelsson and Yasri, 2020). The flocs from the electrochemical coagulation process are much larger and more uniform in size than those produced by chemical coagulation, facilitating their separation via decantation or filtration. The low water content of these flocs, which are resistant to acid compounds, also makes filtration and extraction easier. Flocs move through negligibly small sludge volumes during electrocoagulation, considerably less than during chemical flocculation. It is said that electrocoagulation can efficiently remove small colloidal particles as affected by the electric field, leading to the flocculation and flotation of pollutants (Abbas and Ali, 2018). Many contaminants, including suspended particles, total organic carbon (TOC), oil emulsions, heavy metals, chemical oxygen demand (COD), dyes, and turbidity, can be removed from water or wastewater via electrocoagulation. The advantages of electrocoagulation in wastewater treatment have been thoroughly described in many previous studies (Kobya et al., 2020; Branyikova et al., 2018).

However, this solution presents significant challenges to the electrocoagulation process, requiring additional post-treatment procedures. Therefore, comprehensive research is crucial for integrating electrocoagulation into existing wastewater treatment, improving process efficiency, and overcoming limitations in environmental applications. To the authors' knowledge, there is currently no comprehensive review of stand-alone and hybrid electrocoagulation systems, nor of their development and application in water and wastewater treatment.

The present review is motivated by the need to synthesise and critically contrast recent progress in EC technology, with an emphasis on materials innovation, mechanistic insight, and engineering design. Specific attention is drawn to: 1) novel electrode materials and surface treatments created to manage passivation and improve current efficiency (Reddy, 2024; Estevez et al., 2024); 2) advanced understanding of electrochemical and physicochemical process that leads to the elimination of pollutants and formation of flocs (Bajpai et al., 2021; Qin et al., 2023); and 3) reactor design methods that optimise hydrodynamics, energy efficiency, and scalability (Nyangib et al., 2021; Lopez-Guzman et al., 2021). This review further highlights the growing trend towards integrated or hybrid EC systems (e.g., combining EC with biological, membrane, or advanced oxidation processes) for greater performance and sustainability (Zhang M. et al., 2023; Moed and Ku 2022). In addition to technological issues, this research identifies essential techno-economic and environmental concerns that limit wide-scale implementation, including low energy requirements, electrode degradation, sludge management, and potential production of secondary pollutants (Slama et al., 2021; Das and Nandi, 2020). Solutions entail both material- and process-level innovations, along with the standardisation of assessment protocols and life-cycle studies, to guide future research and policymaking (Shin and Coletti, 2024; Halpegama et al., 2021). Through the systematic integration and critical evaluation of the literature, this review aims to shed light on the current state of research on electrocoagulation, identify outstanding scientific and engineering challenges, and provide a roadmap for a future EC design to ensure efficient, cost-saving, and sustainable wastewater treatment.

Despite extensive research on electrocoagulation (EC) for different wastewater categories, the literature poses difficulties in comparison and generalisation due to inconsistent performance metrics, varied reactor configurations, and frequent neglect of essential operational parameters (e.g., electrode mass loss relative to energy consumption and sludge production), obstructing the formulation of universal design and operational standards.

Furthermore, contemporary review articles tend to focus either on electrochemical principles or on specific wastewater applications. Only a limited number provide a comprehensive and critical synthesis that includes electrode materials, reaction mechanisms, reactor configurations, and practical scale-up challenges (cost, scalability, environmental factors). The document highlights a substantial deficiency: "there is currently no comprehensive review of stand-alone and hybrid electrocoagulation systems" (including their development and application in water/wastewater treatment), emphasising the need for a cohesive, critical analysis of both stand-alone and hybrid EC methodologies and their related implementation obstacles.

## ELECTROCOAGULATION PROCESS

Electrocoagulation is a sophisticated water treatment method that has received considerable recognition for its effectiveness in eliminating pollutants from various wastewater sources, including domestic and industrial effluents. This cost-effective approach involves destabilizing stable emulsions and suspensions in a solution using salt polymers or polyelectrolytes. The elimination of cathodic pollutants in water followed by electro-flotation is a critical reaction that takes place during EC. The hydrogen or oxygen bubbles produced by the electrodes facilitate the elevation of coagulated particles through electro-flotation (Singh and Das, 2018). Figure 2 illustrates the schematic configuration of an EC reactor. The primary operating parameters that affect the EC process include inter-electrode distance, solution pH, electrode type, applied current density, and electrode arrangement. Consequently, it is imperative to improve these operating parameters in every electrocoagulation analysis (Moussa et al., 2017). The electrolysis effect induces chemical and physicochemical events in EC. This indicates that electricity is crucial for the production of coagulants through anodic dissolution, the destabilization of particle and pollutant suspensions, and the formation of flocs through the aggregation of the destabilized phase (Jallouli et al., 2020). The electrocoagulation process depends on electrochemical events, with oxidation, electron loss occurring at the cathode and reduction, electron gain at the anode. The electrocoagulation process produces in-situ coagulants, thus rendering supplementary chemicals unnecessary during treatment (Rao et al., 2001; Chen, 2004).

The electrocoagulation (EC) process, while extensively utilized for water and waste water treatment, presents certain constraints, such as the quick consumption of sacrificial anodes requiring regular, reduction and replacement in process efficiency attributable to electrode passivation. Flocs from electrocoagulation contain high metal ion concentrations that necessitate further treatment, thus combining electrocoagulation with other methods can enhance wastewater treatment sustainability The process of electrocoagulation entails oxidation and reduction reactions, whereby an electric current is applied to an electrolytic solution to destabilising the pollutants (whether suspended, emulsified, or dissolved) (Syam Babu et al., 2020). Due to the relatively non-toxic nature of the iron and aluminium hydroxides generated through precipitation, along with their abundance on Earth, low cost, and high valence, which facilitates efficient pollutant removal, aluminium and iron are the primary electrode materials. Additionally, pollutants can be removed via flotation (the production of hydrogen at the cathode) or by deposition on the cathode electrode resulting from simultaneous cathodic processes. Although electro dissolution should only take place at the anode, the cathode and anode are typically composed of the same metal. EC can be carried out continuously or in batches (Shokri and Nasernejad, 2024).

Electrocoagulation (EC) was considered an obsolete procedure. It was first employed in drinking water purification processes in England in the eighteenth century, whereas wastewater treatment plants began functioning in the United States at the onset of the twentieth century. By the late 1930s, chemical coagulation and biological treatments had predominantly replaced previous methods in wastewater treatment for the elimination of soluble organic pollutants and colloidal pollutants, respectively. The main reason for this was the heightened operational expenditures, especially the cost of energy during this period. Since the 1990s, however, numerous developments have occurred, leading to a "rediscovery" of the advantages of EC (Issaka, 2024).

Table 1 provides a summary of ten benefits found in the literature , outlining the particular disadvantages of EC in contrast to other methods. Electrocoagulation presents more challenges, including the necessity for sludge management, which must be mitigated through chemical coagulation and activated sludge methods. Sludge disposal should be analogous, as the structure of electrocoagulation sludge is similar to that produced through chemical coagulation using either alum or iron chloride. On the other hand, one problem specific to EC is that, as far as we are aware, there are few comprehensive assessments of electrocoagulation modelling and scale-up methodologies for the EC treatment of water (Al-Qodah et al., 2025). Therefore, the purpose of this study is to provide an overview, analysis, and discussion of recent developments in modelling techniques created for EC.

**Table 1.** Advantages and disadvantage of EC

| Advantages | Disadvantages |
|---|---|
| Nonspecific method | Requirement for upkeep |
| Manage potable water and sewage | Passivation of electrodes with time |
| Reduced costs by combining oxidation, coagulation, and precipitation (Sun et al., 2022) | Requirement for high-conductivity water |
| Lesser requirement for chemical reagents (instead of using electrcity and Al or Fe electrodes) | Lack of systematic reactor design (Issaka, 2024) |

## MECHANISM AND KINETICS OF ELECTROCOAGULATION REMOVAL

The electrocoagulation method employs electric current to destabilise contaminants present in the electrolytic solution, either in the form of dissolved or suspended particulates (Titchou et al., 2021). The electrocoagulation process consists of seven fundamental stages: 1) the development of cations from metals by applying electrical current to the anodes; 2) the gener-

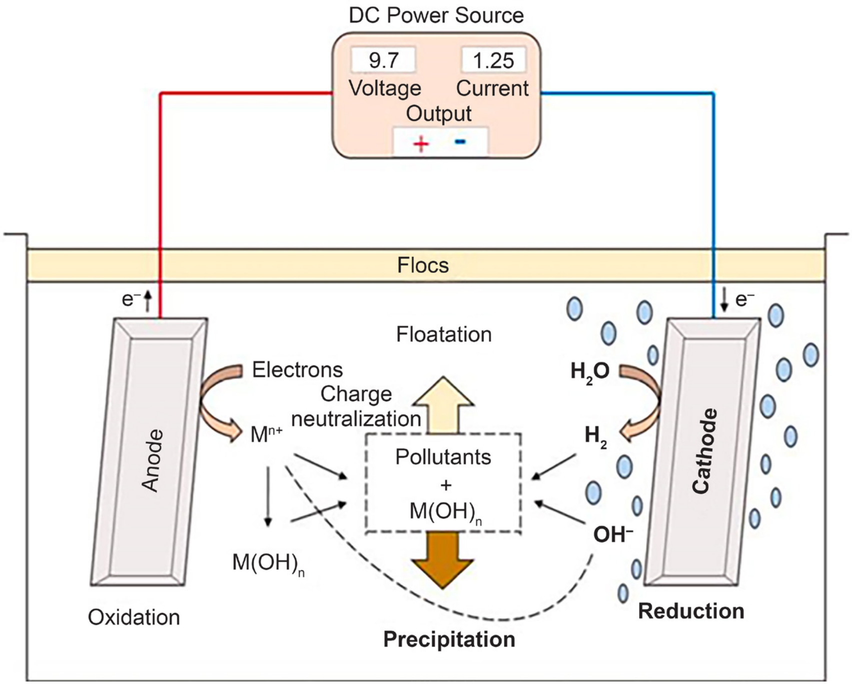


**Fig. 2.** Schematic diagram of the EC process (Adapted from Moussa et al., 2017).

ation of the hydroxyl ions, which are formed through cathodic hydrolysis; 3) the reaction of metal ions with hydroxyl ions to produce metal hydroxides; 4) the oxidation of hazardous contaminants into safe intermediate products; 5) the elimination of contaminant charge through interaction with metal hydroxide compounds; (vi) the adsorption of charge-neutralised pollutants onto metal hydroxides (Deng and Brillas, 2023).

Consequently, adsorption, coagulation, and flotation are the three primary mechanisms responsible for pollutant degradation in the EC system. Figure 3 depicts the mechanism of pollution removal by the EC method (Dindas et al., 2020).

The electrocoagulation compartment enables anodic dissolution. Equation (1) describes the generation of hydrogen gas at the cathode (Equation (2)) and the production of hydroxyl ions at the anode (Equation 3). All of these processes foster the formation of in-situ coagulants. Electrogenerated coagulants facilitate the creation of floc encapsulated in metal hydroxides, serving as effective adsorptive agents (Nidheesh, Khan et al., 2022).

At anode:

$$M(s) \rightarrow M3aq+3 + ne^{-} \quad (1)$$

$$H_2O \rightarrow 4H+aq + O_2\ (g) + 4e^{-} \quad (2)$$

At cathode:

$$nH_2O + ne- \rightarrow n/(2)\ H_2\ (g)+ nOHaq^{-} \quad (3)$$

The dynamics of pollutant removal by electrocoagulation have been studied for over two decades. A kinetic investigation on the removal of heavy metals and suspended solids present within synthetic wastewater using batch electrocoagulation processes was conducted by Singh and Mishra in 2017 (Martinez-Huitle et al., 2021). Research revealed that following 30 minutes of treatment at a current density of 5.3 mA/cm$^2$, the removal efficiencies for heavy metals – copper, zinc, and chromium – were 99%, 82%, and 60%, re-

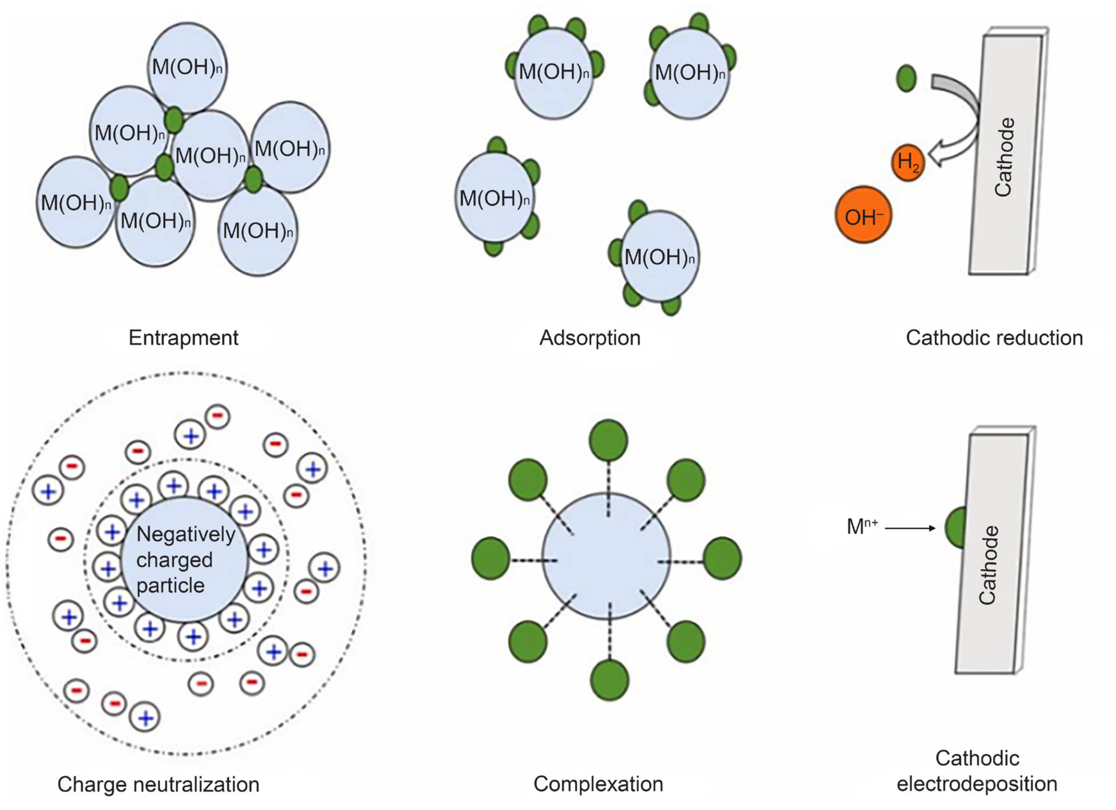


**Fig. 3.** Mechanism of pollutant degradation by electrocoagulation (Source: Dindas et al., 2020)

spectively. The removal efficiency for the total amount of suspended solids (TSS) was 76.5%. Furthermore, the removal of pollutants, affected by treatment duration and flow density, was most accurately represented by the initial and second-order kinetic models. Ahmadian et al. (2012) studied the kinetic behaviour of the batches' electrocoagulation process for treating wastewater from slaughterhouses using eight electrodes (Weerasinghe et al., 2025).

The removal efficiencies of COD, BOD, total nitrogen, and suspended particles were determined to be 93%, 97%, 84%, and 81%, respectively, at an applied current density of 2.5 mA/cm² for a treatment duration of 50 minutes. Kinetic analysis demonstrated that the pollutant removal efficiency conformed to a first-order reaction kinetic model throughout the treatment process.

The kinetics involved in eliminating phosphate from industrial wastewater have been evaluated using the continuous electrocoagulation method (Sayin et al., 2025). Kinetic studies successfully demonstrate the mechanism of chemical processes, identifying rate-controlling phenomena and producing time-dependent predictions about the composition of reaction mixtures. Nonetheless, it is impractical to use kinetic models to examine the adsorption of the pollutant on the surface of Al(OH)3 and its subsequent degradation in wastewater. Furthermore, using a limited dataset for model validation may lead to ambiguity regarding the solubility of solid aluminium hydroxide coagulants. Several key aspects must be considered when adopting response kinetic models during the electrochemical process, including the gas flotation rate, the oxidation state of the electrodes, and the surface coverage. The limitations in heat and mass transport are due to the rapidity of the reaction (Arias et al., 2025).

## APPLICATION OF ELECTROCOAGULATION

The equipment is designed to operate in a simple, economic, and appropriate way for different types of wastewater. This chapter provides an overview of how EC is applied to treat wastewater generated by various industries. The developed equipment utilises the DEP force to stimulate the microalgae growth within marine ecosystems. An innovative design involving asymmetric Al electrodes and an AC source achieved a maximum energy efficiency of 90.9% at 7.1 mA/cm² within a 10-minute electrolysis time. The energy consumption value required to produce one kilogram of microalgae was identified as 4.62 kWh/kg.

According to previous research into optimal operational values, the aluminium content of biomass harvested with alternating current-dielectrophoresis (ACD) was 52% lower than that obtained with alternating current, even though harvesting efficiency remained consistent across both methods (Branyikova et al., 2018).

Producing up to 10 litres of wastewater per litre of milk, the dairy industry is the world's largest consumer of water. Dairy effluent is white, whereas whey is yellowish-green and has produces a notably unpleasant aroma. Dairy wastewater has typically elevated levels of biological oxygen demand (BOD) and chemical oxygen demand (COD), containing substantial quantities of dissolved and dispersed organic substances, including fats, oils, and greases, as well as essential nutrients such as ammonia, phosphates, and other minerals. Furthermore, the dairy wastewater contains significant concentrations of proteins, including casein and whey proteins, as well as detergents and sanitation agents conventionally employed in cleaning operations. These characteristics contribute to elevated BOD and COD levels. This increase is attributable to diminished dissolved oxygen levels. Dairy wastewaters are prone to rapid decomposition, which results in reduced dissolved oxygen concentrations. These effluents are typically discharged into adjacent water bodies or terrestrial areas without any prior treatment, thereby presenting a critical environmental risk (Valente et al., 2015). An experimental study was conducted to evaluate the merits and drawbacks of conventional electrocoagulation (EC) and indirect EC techniques for removing pollutants from dairy waste. Calcium chloride has exhibited remarkable effectiveness as an electrolyte. At a neutral pH of seven, the removal efficiencies for phosphates and turbidity reached an impressive maximum of 95%, while the organic matter persisted in the solution. The solution remained stable for 45 hours after electrocoagulation due to the elevated organic matter content Increased pollutant concentrations in the solution rendered it non-recyclable (Jallouli et al., 2020; Benazzi et al., 2016) .

In terms of the economic viability, traditional EC was identified as the more effective of the two approaches, even though indirect EC was deemed to be the more cost-efficient one. The removal of pollutants from tannery wastewater has become a significant issue due to the environmental risks posed by the unregulated discharge of wastewater into aquatic ecosystems. Tannery wastewater is characterised by its brown coloration, foul odour, high total dissolved solids (TDS), and substantial organic load. It contains alarmingly high concentrations of ammoniacal nitrogen, calcium, magnesium, chlorides, sodium, potassium, sulphates, and sulphides. This type of wastewater poses severe environmental challenges, including eutrophication, increased anaerobic activity, and depletion of dissolved oxygen (DO). Various studies suggest that elevated concentrations of nitrogen compounds contribute to eutrophication, adversely affecting aquatic biomass and biodiversity, inflicting chronic impacts on marine organisms. Tannery effluent contains numerous biodegradable organic compounds, thereby increasing the biochemical oxygen demand (BOD) in aquatic environments. Pollutants associated with tannery operations raise salt concentrations, osmotic potential, total suspended solids, and chemical oxygen demand (COD). Many researchers have documented COD levels in tannery effluent exceeding 2000 mg/l, which significantly surpasses the permissible limit of 1,000 mg/l for discharge into public sewage systems. Thus, it is imperative to treat tannery effluents prior to their discharge to wastewater systems (Rao et al., 2001). Researchers have employed electrocoagulation, ultraviolet photolysis, or a combination of both methods to effectively treat effluent (Jallouli et al., 2020).

The sequential methodology for wastewater treatment, which uses electrocoagulation (EC) alongside ultraviolet (UV) radiation, demonstrates considerable efficacy, achieving a substantial reduction of 94.1% in chemical oxygen demand (COD), and surpassing the individual efficiencies of 85.7% attributed to EC and 55.9% associated with UV (Chezeau and Boudriche, 2020; Chen et al., 2021). Several scholars have investigated the ramifications of introducting air microbubbles into the conventional electrochemical (EC) cells, which usually comprise iron electrodes and a microbubble diffuser for the generation of bubbles (Sruthi et al., 2018; Jin et al., 2016). The researchers conducted a series of empirical experiments and provided recommendations for the optimal configuration of each parameter in order to achieve maximal extraction of contaminants from textile dye compositions. Attempts have been made to design a continuous-flow electrocoagulation reactor for removal of azo dyes, focusing on methyl orange (Wu et al., 2021). The authors utilised folded plate Fe sheets as the cathode and anode in the continuous reaction process. Furthermore, it was documented by (Liu et al., 2022) that the decolorisation rate reached 92.35% when compared to a flat electrode system under analogous conditions (pH, time, current density, etc.).

The study also looked at the effects of plate distance, plate angle, and liquid flow on operational efficiency. All of these exerted a significant influence. Given the widespread presence of fluorides in domestic water supplies exceeding permissible thresholds, which poses substantial health risks, the researchers have sought to eliminate fluorides via electrocoagulation and to evaluate its effectiveness in fluoride removal. The authors procured a sample from various rivers in Tanzania, and simulated a solution to reflect the chemical composition of the river water. Positive results were obtained through the implementation of the tests, leading to the conclusion that EC represents a viable method for substantially reducing elevated fluoride concentrations. The fluoride concentration of 1.5 mg/l is recommended by the WHO and the TBS, a level that can be achieved by the system with a fluoride removal efficiency of 90% (Ewadh et al., 2021). The optimal applied voltage for an effective electrochemical approach to fluoride elimination from water is proposed to reside between 30 and 35 volt (Grich et al., 2019). Microalgae exhibit a diverse range of functionalities that are applicable across various sectors. Microalgae-derived biofuels are regarded as a promising alternative energy source. The aim was to develop an integrated electrochemical system that employs metal-air fuel cells for the cultivation of Nannochloropsis salina (Mahmood et al., 2021; Maitlo et al., 2019).

Several trials were conducted utilizing three kinds of electrodes: Mg, Al, and Fe. Their principal objective was to examine the potential of harvesting marine microalgae for the analysis of metal-air fuel cell electrochemical (EC) systems and to compare the electricity generated during the EC process with fuel cells against that produced by a conventional power source. The findings indicated that the metal-air fuel cell system outperformed the conventional EC system. Among the tested metals, magnesium was the most efficient anode, whereas the other metals showed shorter hydraulic retention times and higher algal biomass production. Significantly, a considerable amount of research has been conducted on the treatment of palm oil mill effluent. However, its detrimental characteristics in relation to the management of hazardous waste, particularly palm oil mill effluent (POME), which contains impurities analogous to those found in olive mill waste water, are a concern. A recent study examined the elements influencing floc production and the effectiveness of floc removal, including electrolysis duration, current densities, electrode spacing, and pH levels. The authors chose to utilise a light microscope to examine the dimensions and configurations of the flocs.

Furthermore, electrocoagulation (EC) can be efficiently employed for the treatment of various textile effluents, achieving satisfactory removal efficiencies. Effluents from textile manufacturing are generally defined as wastewater that exhibits high coluor concentrations due to leftover dyes, chemical oxygen demand (COD), salinity, high temperatures, and a wide-ranging pH. Moreover, textile effluents may contain chemicals that are carcinogenic, toxic or mutagenic to many microbial species. The effectiveness of treating textile effluents has been shown to be 76% for chemical oxygen demand (COD) and 95% for colour (Tyagi et al., 2014). Hospital wastewater, for example, is biologically resistant and does not lend itself to simple biological treatment. Hospital effluents contain suspended solids, heavy metals, pharmaceuticals, high pH levels, COD, and numerous other contaminants. Pharmaceuticals production facilities and hospitals are two main sources of highly concentrated contaminated wastewater that cannot be effectively treated by conventional biological methods.

In such instances, EC has proven to be a viable alternative. Researchers have employed electrochemical technologies to conduct extensive studies aimed at removing antibacterial agents such as ciprofloxacin. One study found that aluminium electrodes paired with NaCl electrolyte under specific conditions can remove up to 88.75% of pollutants from wastewater. For wastewater, a removal efficiency of 58.3% was observed with an inter-electrode distance of 10–15 mm. Electrocoagulation proves effective for treating wastewater that contains emerging pollutants, such as $TiO_2$2-based nanoparticles, which are increasingly used in the pharmaceutical, food, and technology sectors. However, these nanoparticles can be harmful to human health by penetrating red blood cells and damaging DNA. Recent research has focused on creating an effective electrochemical reaction cell to eliminate trinitrophenols (TNPS) from wastewater. This cell relies on iron electrodes and hydrochloric acid as the electrolyte, and has an optimized interelectrode distance of 2 cm. Under neutral pH and a current of 100 mA, the system achieves over 95% removal efficiency of TNPS. Meanwhile, microplastics – tiny plastic particles resulting from the degradation of consumer and industrial waste – have become a significant environmental concern. Due to their small size and low density, microplastics are easily ingested by aquatic organisms, causing physical harm such as stomach abrasions and blockages. Toxic substances linked to microplastic waste can severely damage organisms that can also affect humans who consume these organisms at higher levels of the food chain. Studies have been carried out to remove microplastic waste from wastewater using EC technology (Ghanbari et al., 2020). Two particulate microplastic materials (polyethene poly-methylmethacrylate) and two fibrous microplastic materials (cellulose acetate obtained from polypropylene and cigarette butts obtained from disposable surgical masks) materials were tested. Iron and aluminium acted as anodes, while copper was used as a cathode material. Anhydrous $Na_2SO_4$ was initially added to the solution to server as an electrolyte. A 2 cm distance was maintained between a pair of electrodes. Removal efficiency of the Al anode was found to be higher for all microplastic materials tested, i.e. over 98.6%. The removal effect due to microplastics was found to be highest at an initial influent material pH of 7.2. Final efficiencies of 93.2% for Pe, 91.7% for PM, 98.2% for CA, and 98.4% for Pp microplastic materials were achieved by (Shen et al., 2022).

Electrocoagulation (EC) has become widely used due to its high efficiency in removing a broad range of organic and inorganic pollutants from wastewater. It is extensively utilized across multiple industries, including the pulp, automotive, municipal, paint, and petroleum sectors, for treatment effluents. Detailed experimental conditions required to optimize pollutant removal efficiency for different wastewater types are summarised in Table 2.

**Table 2.** Applications of electrocoagulation (Ec) in wastewater treatment

| Reference | Wastewater type | Electrodes (anode/cathode) | Experimental conditions | Removal efficiency (%) |
|---|---|---|---|---|
| (Tabash et al., 2024) | Dairy wastewater | Al–Al | Applied current density: 6.16 mA/cm²; reaction time: 25 hr; pH: 5.0 | COD = 57.0 |
| (Kobya et al., 2020) | Textile effluent | Fe–Fe | Current density: 14.0–17.0 mA/cm²; electrolysis time: 20 hr; spacing between electrodes: 4 mm; pH: 8.5 | COD = 76.0; Colour = 95.0 |
| (Hawari et al., 2015) | Hospital wastewater | Al–Al | Reaction duration: 20 hr; electrode spacing: 1 mm; pH = 7.78 | Ciprofloxacin (CIP) removal = 88.57 |
| (Nasrullah et al., 2020) | Industrial wastewater | Al–Fe | Current density: 12.5 mA/cm²; reaction time: 60 hr; pH = 7.8 | COD = 99.0; BOD = 99.0; Colour = 100.0; Turbidity = 100.0 |
| (Titchou et al., 2021) | Tannery wastewater | Ti–$MnO_2$ | No. of electrodes: 2; spacing: 4 mm; current: 0.10–0.60 A; time: 20 hr; pH = 8.0 | Colour = 75.0–95.0; COD = 50.0–75.0; Ammonia = 96.0 |
| (Tyagi et al., 2014) | Municipal wastewater | Stainless steel | Electrode spacing: 5 mm; current: 0.8 A; reaction time: 5 hr; pH = 6.54 | SS = 94.80; BOD = 98.0 |
| (Ahmadzadeh et al., 2017) | Landfill leachate | Fe–Fe | Current density: 4.8 mA/cm²; reaction time: 180 hr | COD = 65.85 |
| (Singh et al., 2016) | Automobile wastewater | Cu–Al | pH = 6.0; reaction time: 40 hr; current density: 2.5 mA/cm² | Grease & oil = 92.5; Turbidity = 99.0; COD = 95.10 |
| (Ghanbari et al., 2020) | Paper recycling wastewater | Fe–Al | Voltage: 10 V; pH = 7.0; reaction time: 60 hr | Ammonia = 85.50; Color = 85.0; COD = 79.50; TSS = 83.40 |
| (Shen et al., 2022) | Paint industry effluent | Fe–Fe | Current density: 14.2 mA/cm²; pH = 6.6–7.15 | Aluminium = 79.80; COD = 68.0 |
| (Al-Qadah et al., 2020) | Bio-diesel wastewater | Fe | Current density: 0.3226 mA/cm²; pH = 6; reaction time = 6 hr | COD = 91.74; TSS = 91.98 |
| (Branyikova et al., 2018) | Ayurveda pharmaceutical wastewater | Al – Stainless steel | Electrode distance: 8.5–9.5 mm; voltage: 10–10.5 V; pH = 4.0–10.0; time: 30–150 hr | Color = 97.83; COD = 58.35 |
| (Bazrafshan et al., 2015) | Marigold wastewater | Fe–Fe | Current = 2.9 A; pH = 6.5 | TOC = 76.0; TP = 83.0 [84] |
| (Bouguerra et al., 2015) | Domestic wastewater | Al–Al Fe | Electric current = 1.65 A; reaction time = 25 hr; pH = 6.0 | Turbidity = 98.0; COD = 92.0 |
| (Rahman et al., 2021) | Petrol refinery wastewater | Fe–Fe | Current density = 13.4 mA/cm²; voltage = 3.2 V; reaction time = 360 hr; pH = 5.0–8.0 | Selenium = 90.0 |
| (Bener et al., 2019) | Potato chip wastewater | Al–Fe | Current density: 2.0–3.0 mA/cm²; spacing = 2 mm; pH = 4.0–6.0; temperature = 22 °C | Turbidity = 98.0; BOD not mentioned |

| Reference | Wastewater type | Electrodes (anode/cathode) | Experimental conditions | Removal efficiency (%) |
|---|---|---|---|---|
| (Mousazadeh et al., 2021) | Baker's yeast wastewater | Al–Fe | Electrode spacing: 2 mm; connection type: MPP; current = 7.0 mA/cm²; pH = 7.0 | COD = 71.0; Turbidity = 90.0; TOC = 52.0 |
| (Sediqi et al., 2021) | Industrial oil-in-water emulsion | Al – Stainless steel | Electrode spacing = 3 mm; pH = 7.0; temperature = 20°C | COD = 90.0; Turbidity = 99.0 |
| (Bayramoglu et al., 2004) | Machinery industry wastewater (coolant) | Al–Al | Current density: 20.0 mA/cm²; electrolysis time: 30 hr | COD = 68.0 |
| (Eryuruk et al., 2018) | Electroplating wastewater | Fe–Fe | Electrode spacing: 1 mm; current density: 3.0–6.0 mA/cm²; temperature: 25°C | Ni = 99.1; COD not mentioned |

## MATERIALS USED FOR ELECTRODES IN ELECTROCOAGULATION

### Aluminium and iron

Aluminium (Al) is frequently used as a material for electrodes in electrochemical processes. The application of a current density generates aluminium cations ($Al^{3+}$) as the sacrificial anode dissolves (Maitlo et al., 2019). The anodic and cathodic reactions occurring with aluminium electrodes are illustrated in equations (4)–(6). The metal concentration in the solution increases through electro-dissolution and eventually precipitates in the EC chamber as metal hydroxides. The $Al^{3+}$ ions are in a complex equilibrium with many polymeric and monomeric species, such as $Al(OH)_3$, $Al(OH)_2^+$, $Al(OH)_4^-$, $Al_6(OH)_{15}^{3+}$, $Al_7(OH)_{17}^{4+}$, $Al_8(OH)_{20}^{4+}$, $Al_{13}(OH)_{34}^{5+}$, and $Al_{13}O_4(OH)_{24}^{7+}$, depending on the pH of the solution. Notably, $Al(OH)_3$ derived from a complex precipitation process is responsible for forming flocculates and aggregates (Nidheesh and Singh, 2017).

$$\text{At anode surface: } Al \rightarrow Al^{3+}\,(aq) + 3e^- \quad (4)$$

$$\text{Al cathode surface: } 3H_2O + 3e^- \rightarrow \frac{3}{2}\,H_2(g) + OH^- \quad (5)$$

$$\text{Overall: } Al^{3+}\,(aq) + 3H_2O \rightarrow Al(OH)_3 + 3H^+ \quad (6)$$

Similarly, the application of an external potential across iron (Fe) electrodes generates in-situ coagulants through the electro-dissolution of sacrificial electrodes. Hydroxyl ions are produced at the anode through reduction, while $H_2$ bubbles are produced at the cathode through oxidation, causing the resultant floc to rise to the surface of the water. The anode and cathode reactions with Fe electrodes are given in equations (7)–(9) (Maitlo et al., 2019). At low solution pH and oxygen-ionised water, the ferrous ions are easily oxidised to ferric ions. Depending on the pH, the electrogenerated ferric ions undergo a hydrolysis reaction, to produce different monomeric and polymeric species in the solution, such as $Fe(OH)_3$, $Fe(H_2O)_5OH^{2+}$, $Fe(H_2O)_6^{3+}$, $Fe(H_2O)_4(OH)_2^+$, $Fe(OH)_4^-$, $Fe_2(H_2O)_6(OH)_4^{2+}$ and $Fe_2(H_2O)_8(OH)_2^{4+}$. These Fe complexes have an extremely high tendency to polymerise within pH range of 3–7. The major complex formed, $Fe(OH)_3$, continues to exist as an amorphous suspension in the aqueous solution, and therefore allows for the removal of wastewater pollutants by either electrostatic attraction or complexation reaction followed by coagulation (Ilhan et al., 2019).

$$\text{At anode surface: } Fe(s) \rightarrow Fe^{3+} + ne^- \quad (7)$$

$$\text{At cathode surface: } 2e^- + 2H_2O \rightarrow H_2 + 2OH^+ \quad (8)$$

$$\text{Overall: } 4Fe + 10H_2O + O_2(aq) \rightarrow 4Fe(OH)_3(s) + 8H^+ \quad (9)$$

### Alternative electrode materials

In addition to Al and Fe electrodes, copper (Cu) can also be employed as an electrode material to assist in the removal of wastewater contaminants in electrocoagulation. A comparison of Al and Cu electrodes demonstrated that Cu electrodes could achieve much greater removal efficiencies than Al electrodes. Uniform corrosion was registered on the Cu electrode surfaces after treatments. Using Cu electrodes for electrocoagulation processes is accompanied by the usual $H_2$ evolution at the cathode and the release of $Cu^{2+}$ ions at the anode. The reactions involved in the electrocoagulation process with Cu electrodes are shown in equations (10)–(12), in which $Cu^{2}+$ ions are generated in situ to act as coagulants for contaminant removal (Nasrullah et al., 2020). The hydrolysis of $Cu^{2}+$ and $Cu^{3}+$ ions produces monomeric and polymeric species, such as $CuOH^{2+}$, $Cu(OH)_2^+$, $Cu(OH)_4^-$, $Cu_2(OH)_2^{4+}$, $Cu(H_2O)^{2+}$, $Cu(H_2O)_4(OH)_2^+$, and $Cu(H_2O)_5OH^{2+}$ (Nasrullah et al., 2020).

Microplastics are extremely fine particles of plastic waste that are found in the environment as a consequence of dumping and degradation of consumer and industrial waste. Due to their lower density and size, microplastic particles can easily be ingested by aquatic organisms that eventually suffer from stomach abrasions and microblockage. Toxic substances linked to microplastic waste can cause severe damage to organisms, which in turn can also affect humans, who consume these organisms at higher levels of the food chain. Several studies have investigated the use of EC technology to remove microplastic waste from wastewater (Ghanbari et al., 2020). Two particulate microplastic materials (polyethene (Pe) and poly-methylmethacrylate (PM)) and two fibrous microplastic materials (cellulose acetate (CA) obtained from cigarette butts and polypropylene (Pp) obtained from surgical masks made of disposable material) were tested. Fe and Al metals acted as anodes, while copper was taken as a cathode. Anhydrous $Na_2SO_4$ was initially added to the solution and taken as electrolyte material. A2 cm distance was maintained between a pair of electrodes. Removal efficiency of Al anode was found to be higher for all tested microplastic materials, i.e. higher than 98.6%. The removal effect due to microplastics was found to be the highest at an initial pH of influent materials of 7.2. Final removal efficiencies of 93.2% for Pe, 91.7% for pmma, 98.2% for CA, and 98.4% for Pp microplastic materials were achieved (Shen et al., 2022).

$$\text{At anode surface: } 2Cu \rightarrow 2Cu^{2+} + 4e^- \quad (10)$$

$$\text{At cathode surface: } 4H_2O + 4e- \rightarrow 2H_2 + 4OH^- \quad (11)$$

$$\text{Overall: } 2Cu + 4H+ \rightarrow 2Cu^{2+} + 2H_2 \quad (12)$$

Moreover, some researchers have suggested using different anodic materials, such as magnesium (Mg) and zinc (Zn), for electro-coagulation. This approach is the same as the one indicated earlier for Al, Fe, and Cu electrodes, involving anodic dissolution (equations 13 and 14), followed by precipitation and coagulation. Depending on the pH of the solution, the result are ions of $Mg^{2+}$ and $Zn^{2+}$ form hydroxides of $Mg(OH)_2$ and $Zn(OH)_2$ (equations 15 and 16) (Singh et al., 2022).

Al and Fe ions have a higher charge valence compared to Mg and Zn ions, which facilitates coagulation with a minimal dosage of coagulant. The evaluation of alternative electrochemically generated coagulants depends on the concentrations of coagulant residues determined in the treated water. The U.S. Environmental Protection Agency (US EPA) advises maintaining aluminium concentration at 0.2 mg/l and establishing a magnesium limit of 30 mg/l to prevent potential health issues.

$$Mg \rightarrow Mg^{2+} + 2e^- \quad (13)$$

$$Zn \rightarrow Zn^{2+} + 2e^- \quad (14)$$

$$Mg^{2+} + 2H_2O \rightarrow Mg(OH)_2\,(s) + 2H^+ \quad (15)$$

$$Zn^{2+} + 2H_2O \rightarrow Zn(OH)_2(s) + 2H^+ \quad (16)$$

Aluminium and iron electrodes are preferred over other electrodes in the electrochemical mechanism as they are economical, widely available, and very effective in removing pollutants. Al and Fe electrodes perform better due to a smaller electrical double layer – the charge valency of $Al^{3+}$ and $Fe^{3+}$ ions is higher compared with copper, zinc, and magnesium. Electrodes enhance the coagulation-flocculation process. Although Fe electrodes lower the cost of the EC process compared to Al electrodes, they can turn the treated EC samples reddish-brown, creating a turbid solution. The aluminium electrode has a better strength-to-weight ratio, is resistant to corrosion, and has better electrical conductivity. Furthermore, the use of Al does not colour the treated solution and can far exceed the Fe electrode in wastewater removal efficiency. When choosing electrode materials, the targeted contaminants and cost-benefit ratios should be taken into account. In addition, both Al and Fe electrodes undergo electrode passivation, which significantly reduces the effectiveness of the electrochemical process. Thus, future research should focus on the implementation of self-cleaning techniques for the electrodes to eliminate the issue of electrolyte passivation.

## IMPACT OF OPERATIONAL PARAMETERS ON THE ELECTROCOAGULATION PROCESS

Understanding the influence of operational elements on the electrocoagulation process is essential for achieving maximum efficiency.

### Current density

The parameters controlling the electrocoagulation mechanism and the resulting process performance are presented in Figure 4. Current density, or the current applied per effective electrode area, is regarded as one of the most important parameters controlling electrocoagulation performance. Current density regulates the electron release rate, which is a consequence of metal ions being released from the electrodes in the EC process. The range of the current density used may vary according to the nature of the effluent. The variation in current density is, in most cases, a result of variations in ionic interactions, which occur due to the nature of pollutant present in the effluent (Ilhan et al., 2019).

In general scenarios, the applied current density for the EC process typically ranges between 0.01 and 880 $A/m^2$ (Shen et al., 2022; Al-Qodah et al., 2020). Even though the applied current density adequately replicates metal ion release and solution dissociation, there is always the risk of excess current that can significantly reduce the EC process efficiency by intensifying in situ secondary reactions as well as the formation of colloidal charge reversal due to overdosing of coagulants. This will shorten the electrode life span and reduce the efficiency of the process. Thus, the current density is a critical parameter forreaching the required treatment efficiency in the EC process (Nidheesh and Singh, 2017). The influence of current density on different types of pollutant-laden wastewater has been observed by several researchers (Bazrafshan et al., 2015; Bouguerra et al., 2015). Rahman et al. (2021) indicated that an applied current density of 25 $A/m^2$ is sufficient to achieve 98.5% COD removal efficiency, accompanied by a significant drop in pollutant removal efficiency at a lower current density of 5.99 $A/m^2$. This is because of the higher $Al(OH)_3$ content in the electrolyte at a higher current density of 25 $A/m^2$, which enhances the coagulation and flocculation processes. Furthermore, a higher current density is beneficial as it results in a smaller bubble size, which further contributes to the easy removal of pollutants by hydrogen flotation (Rahman et al., 2021). Bener et al. (2019) investigated the influence of varying current density on the reduction efficiency of TOC using actual textile wastewater (Bener et al., 2019). They observed that an optimized current density of 100 $mA/cm^2$ was preferred for maximum removal of TOC. In contrast, a low current density of 12.5 $mA/cm^2$ leads to a significant drop in removal efficiency. The study revealed that enhancing the current density from 12.5 to 100 $mA/cm^2$ increases the TOC removal efficiency from 10% to 22.5% within two hours of treatment. Moreover, Mousazadeh et al. (2021) provided an overview of the effects of different operating factors on the removal efficiency of EC in wastewater with high COD pollution levels (Mousazadeh et al., 2021). According to the study, higher current density values lead to increased COD removal rates. At higher current densities on electrode surfaces, the removal of coagulants and the increased production of bubbles enhance contaminant destabilisation, allowing molecules to be destabilised more rapidly. For example, increasing the current intensity ranging from 1 to 25A improved the EC removal efficiency of higher COD (25,000 $mg \cdot l^{-1}$) palm oil mill wastewater (POME) significantly. The removal of COD, BOD, as well as SS, by EC is estimated to be 96%, 94%, and 95%, respectively, at an optimized time of 50 min (Sediqi et al., 2021).

In another study, Bayramoglu et al. (2004) treated the concentrated (29,000 $mg \cdot l^{-1}$) poultry slaughterhouse wastewater using Al and Fe electrodes, The study showed a maximum oil (98%) and COD (94%) removal percentage in 25 min, by increasing current density from 20 to 150 $A/m^2$. Electrocoagulation has also been used by Eryuruk et al. (2018) to treat poultry slaughterhouse wastewaters that have high COD values (9000 $mg \cdot l^{-1}$). The study focused on evaluating the effectiveness of the EC process at different variations of current density (30–50 $mA/cm^2$). The authors observer a maximum COD removal efficiency of 96% in 40 minutes of treatment time at a current density value of 50 $mA/cm^2$.They also established that a high current density value ensures efficient removal of highly COD-contaminated wastewaters using an EC process. An increased current density value is associated with an increased efficiency of pollutants.

It is crucial to remember that an excessive current density may cause secondary reactions and colloidal charge reversal. This may lead to increased electrode depletion and the formation of thin film on the surface of the electrodes, which significantly reduces process efficiency. Therefore, the current density must be optimised against the target effluents. Additionally, the application of higher electrode surface area at lower or optimal current density can address the aforementioned issues.

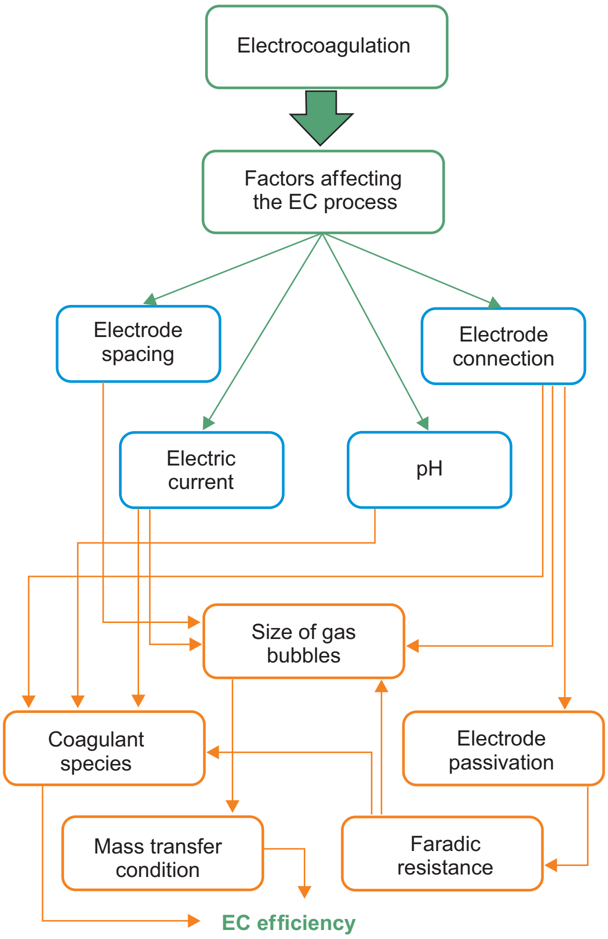


**Fig. 4.** Parameters affecting the mechanism of EC process (Source: own studies)

## IMPACT OF PH LEVEL

The pH levels affect the hydrolysis of metals produced in the reactive environment and determines the main electrochemical mechanisms. This makes it a vital factor in assessing electrochemical performance, particularly with regard to the coagulation mechanism (Reddy, 2024). Additionally, the pH in solution is a critical factor in determining the ED process performance.

The impact of pH correlates with the generation of coagulants in solution, which utilise several types of disproportionated species at equilibrium, e.g., a metal ionic complexes, monomers, polymers, etc. It is important to note the diversity and the number of ionic complexes available in an aqueous solution, as they exhibit different behaviours with respect to the wastewater contaminants that impart different coagulating properties. For example, the species present in highly alkaline media for Fe and Al electrodes, namely, $Fe(OH)_4^-$ and $Al(OH)_4^-$, respectively, demonstrate a poor adsorption capacity (Bukhari, 2008). Conversely, Fe $(OH)_3^-$ and Al $(OH)_3$ that are enhanced in neutral and slightly basic/acidic regions show an improved adsorption ability for the coagulants. The pH of the solution therefore has a profound impact on the physiochemical characteristics of the coagulants, namely (1) the particle size of the species in each coagulant, (2) solubility, and (3) the electrical conductivity of the metal hydroxides (Kim et al., 2002; Vasudevan et al., 2011).

Analyzing the speciation of iron and aluminium resulting from the hydrolysis of their respective ions in the equilibrium state is essential to understand the influence of pH on electrocoagulation processes. Adsorption and coagulation are contingent upon pH values. The adsorption of dissolved monomeric species onto the corresponding hydroxide precipitates determines the apparent surface charge of aluminium or iron precipitates. Electrostatic interactions can elucidate the behaviour of pH-dependent coagulation species and their associated contaminants, given their surface charge. Jiménez et al. performed an extensive investigation into the techniques of two-layer compression, neutralisation, and sweeping flocculation techniques for aluminium and iron electrocoagulation in order to improve the elimination of various contaminants depending on the predominant hydrolysed metal species (Aghapour et al., 2022). The Nernst equation, which governs the thermodynamic behaviour of electrochemical systems, also highlights the critical role of pH in Ec performance. It allows the construction of an pH diagram for a given electrode material, and when it is superimposed on the pH diagram of water, the Pourbaix diagram is generated. This diagram defines the thermodynamically stable regions of metallic species in aqueous environments, including immunity, passivation, and corrosion. By identifying stable aquatic species within a specified range of electrical potential and pH range, one may anticipate the corresponding electrode stability and solubility in water. Zongo examined the speciation of aluminium and iron in order to ascertain the respective preponderance diagrams of the hydroxides and to evaluate a subset of insoluble hydroxides in relation to pH, concentrating only on monomeric species (Estevez et al., 2024). Furthermore, the net charges and associated electrostatic interactions of the contaminants are directly influenced by the protonation/deprotonation of the respective functional groups, depending on pKa values. Ultimately, these conditions affect the double layer, and thus they influence the differences in coagulant formation. Therefore, optimising the solution pH based on the targeted contaminants' nature is required (Ganesan et al., 2013). For instance, Bener et al. (2019) demonstrated the effect of three different pH values (5, 8, and 10) on the TOC removal efficiency achieved from real textile wastewater using Al electrodes (Bener et al., 2019).

The amount of insoluble aluminium hydroxide associated with the Al electrode increases notably as the pH rises from 4.5 to 7, causing negative effects to aluminium hydroxide ions, whereas the reverse process occurs within the ph range of 7 to 10. Amorphous metal hydroxide is not stable beyond the specified pH level (Estevez et al., 2024; Bajpai et al., 2021).

When the pH ranges from 4 to 7, the amount of insoluble iron hydroxide for the Fe electrode significantly increases. The dominance diagram shows that iron hydroxide ions are not present in this latter pH range. These diagrams were produced using a theoretical calculation of the pH and equilibrium constants for both electrode metals at a concentration of 10−12 m. Following EC treatment, the pH of acidic influents will increase. The buffering effect of electrocoagulation may reduce the levels of alkaline effluents (Phu et al., 2025). The removal efficiency of TOC was also affected by the solution's pH. The highest TOC (65%) removal efficiency was recorded at pH 5. When increasing the solution pH up to 10, the removal efficiency decreased significantly. The two possible reasons for the reduced removal efficiency of EC at higher concentrations (pH 10) could be explained by the following: (a) the $Al(OH)_4^-$ species, which predominates in highly alkaline regions at Al electrodes, is not very effective in removing TOC due to its reduced adsorption efficiency; (b) excess $H_2$ gas is likely present near the cathode. On the other hand, Irdemez et al. (2006). demonstrated the influence of varying pH on the removal efficiency of phosphate from synthetic wastewater using Fe electrodes. It was noted that there is a significant reduction in the power consumption in the EC method at a low solution pH (3–4). The optimum pH range for the highest removal efficiency (93%) is given in the range of 6–7, the lowest solubility of $Fe(OH)_2$. Conversely, Demirbas and Kobya (2017), highlighted the treatment of metal-working fluids wastewater using Fe-De and Al-Al electrode systems with various values of solution pH. It can be inferred that the optimum results for the Fe electrode system is obtained at a higher pH of 7.5, whereas a better result is obtained for Al electrodes at a higher pH of 6.5. The two electrodes performed better at neutral pH, and a statistically significant difference was observed between the electrodes in the same wastewater treatment. This indicates that pH of the solution has a significant influence on the performance efficiency of the EC treatment. The pH of the solution in EC method largely affects the release formation of the coagulant species during the treatment method (Demirbas and Kobya, 2017). The formation of $H_2$ in the vicinity of the cathode region increases the alkalinity of the solution due to the formation of $OH^-$ ions. When the pH is unsuitable, this affects the double layer, and therefore the formation of the coagulant. In addition, under highly alkaline conditions, the production of the monomeric polymeric species lowers the adsorption ability. Accordingly, pH levels must be effectively controlled in order to improve the pollutant adsorption ability of the coagulant species in the EC process. In acidic conditions, hydrogen evolution at the cathode raises the pH level. Conversely, secondary processes such as the oxidation of water, the chlorine generation, and its hydrolysis result in a decrease of the pH. The secondary reactions provide hydroxide precipitates that release $H^+$ ions near the anode. This underscores the buffering capacity of EC, which functions concurrently with water alkalinity. This impact is more pronounced with aluminium electrodes due to the generation of aluminium anions at a high pH of 9. Bicarbonate alkalinity has been demonstrated to moderately enhance pollutant removal efficiency (Qin et al., 2023). Furthermore, it facilitates the precipitation of $CaCO_3$ to reduce hardness due to the hydroxyl ions generated by the reduction of water in the area surrounding the cathode.

## IMPACT OF INTER-ELECTRODE SPACING

The inter-electrode spacing represents a key parameter in EC system design, which affects the anode-cathode electrical field strength. Spacing of the electrodes controls the strength of the electrostatic interaction, and consequently, ion migration, coagulant production, and the removal efficiency of the pollutants. Decreasing the distance between the electrodes intensifies the electrostatic field, enhancing the production of metallic ions and metal hydroxides. However, too high intensity of the field results in higher collision between the flocs of the hydroxides and the partial destabilisation of the latter. Nonetheless, the application of a lower inter-electrode distance remains a favourable method, and it is typically correlated with a higher removal efficacy due to the increased coagulant formation rate and higher electrode chemical activity (Branyikova et al., 2018).

However, as the distance between electrodes grows, the electrostatic force declines, and the rate of metal hydroxide floc production, which plays the role of pollutant aggregation, slows down. Increasing the spacing also means increased electrical resistance that translates to higher power input required to maintain current flow between the electrodes (Eryuruk et al., 2018). Thus, the inter-electrode spacing should be kept at an optimal level in order to balance system efficiency and energy costs.

Based on numerous studies, the electrocoagulation process for eliminating contaminants from different types of wastewater is optimised when the electrode spacing remains between 0.5 and 1.0 cm. Rahman et al. (2021) demonstrated that galvanised iron electrodes spaced at 0.5 cm have effectively removed turbidity, colour, and total organic carbon from peat water. Similarly, Maitlo et al. (2019) and Sari-Erkan (2019) found that aluminium electrodes with 1 cm spacing achieved high removal rates for turbidity, total organic carbon, chemical oxygen demand, and colour.

At larger electrode spacings, mass transfer limitations arise caused by reduced movement of the hydroxides off the surface of the electrode into the bulk of the solution, inhibiting their reaction with contaminants. This trend was echoed by the study of Akarsu et al. (2016) and Aswathy et al. (2016), who examined the influence of electrode spacing on the treatment to bilge waste water. Akarsu et al. (2016) only realized 52% cod removal upon 90 minutes of treatment using 8 cm spacing, while 89.9% cod removal was achieved by Aswathy et al. (2016) upon 120 minutes of treatment using 1 cm spacing. The significant disparity in efficiency was determined by the difference in electrode distance and the role it played upon charge transfer and coagulant formation.

Significantly, the importance of keeping the inter-electrode distance short is again reiterated by works involving the treatment of high-strength wastewaters. Reducing the distance between lower electrodes resulted in lower ohmic losses and higher coagulant production rates when decolorising COD-rich effluents (Kobya et al., 2020). Similarly, the treatment of oil-tanning wastewater with an initial 25,000 $mg \cdot l^{-1}$ COD showed the highest cod removal efficiency (> 90%) within 15 minutes when treated with 10–15 mm spacing (Demirbas and Kobya, 2017). The optimal values for the treatment of rice-grain distillery wastewater with an initial 11,500 $mg \cdot l^{-1}$ COD, where 90% COD and 86% colour removal were found with 10 mm spacing and 17.85 $mA/cm^2$ current density. Generally, the inter-electrode spacing plays the key role of affecting the physical and electrochemical processes governing the EC process. Although higher spacings are associated with higher resistance and energy requirements through reduced charge and mass passage, reduced spacings result in higher coagulant species generation and movement, providing higher removal efficiencies of pollutants. Thus, adopting optimal spacing of electrodes, generally between 0.5 and 1.5 cm, is advisable for the best feasible balance between the execution of the processes and energy requirement, improving the technical and economic viability of the systems of electrocoagulation treatment (Ahmadzadeh et al., 2017).

## EC REACTOR DESIGN

The design of electrocoagulation reactors is crucial as it impacts functional parameters – flow system, floc formation, elimination yield, and flotation/settling characteristics – which in turn translate to the overall efficacy of the electrocoagulation process (Libber et al., 2025).

The two main criteria that have been followed in the design of EC reactors are the operating mode and the objectives to be met. According to a literature review, there are three main ways to categorise EC reactor designs.

The primary consideration is the supply mode, i.e. whether the reactor is designed as a continuous or batch system. In a continuous system, reactors are consistently fed with wastewater or water, while in a batch system, a specified volume of effluent is used for every treatment cycle.

The second difference, as seen in Figure 5 (Das and Nandi, 2020), concerns the technique employed to separate the aggregated contaminants. The final difference is the electrode geometry design, which determines the cell's current distribution. Mollah et al. (2004) studied common EC cells, which they have not changed much in the past ten years. Rectangular cells continue to dominate in practice due to the utilisation of planar rectangular electrodes.

The open vertical-plate cell is the most often utilized design in ordinary applications, typically followed by a settler (sedimentation tank) (Fig. 5).

This means that the tank is open at the highest point, inhibiting immersed connections and facilitating servicing. Vertical anodes and cathodes are uniformly arranged in series, and scaling up is straightforward due to the flexibility of any vertical/horizontal length ratio. However, ratios below a value of two enhance maintenance efficiency. The symmetry of the anode-cathode

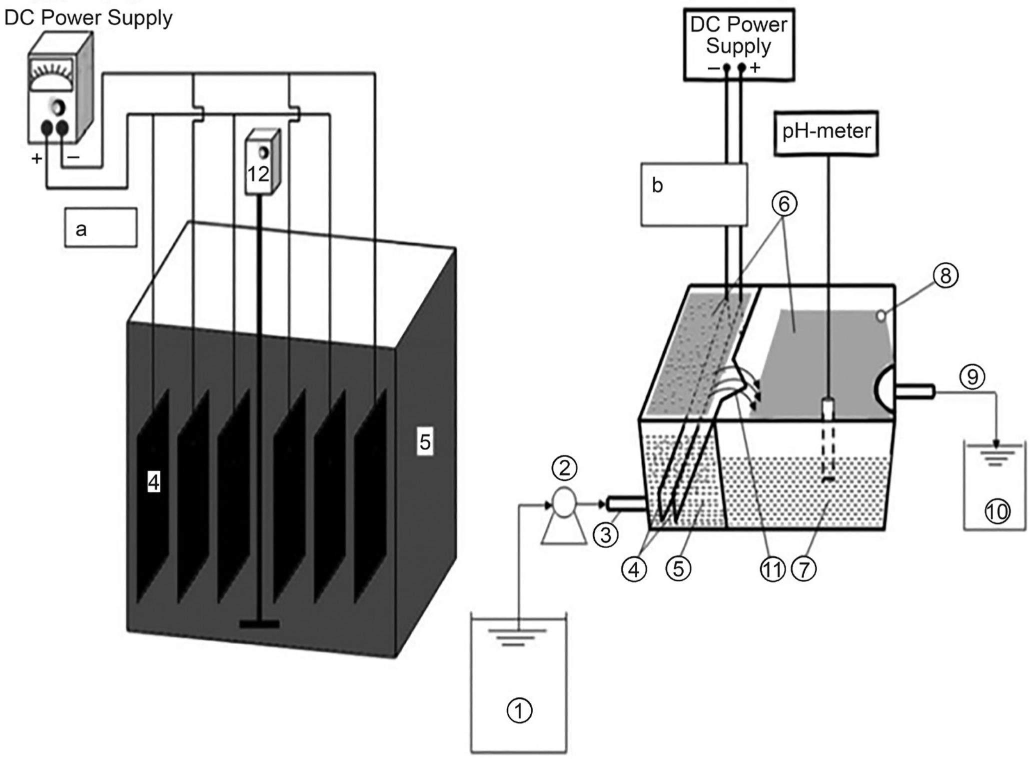


**Fig. 5.** The experimental design: (a) batch electrocoagulation cell (b) continuous electrocoagulation cell (1 – wastewater reservoir; 2 – peristaltic pump; 3 – influent to initial compartment; 4 – electrodes; 5 – electrocoagulation cell / treatment in the first compartment; 6 – sludge; 7 – treatment in the second compartment; 8 – sludge removal; 9 – treated effluent discharge; 10 – treated water reservoir; 11 – outfall; 12 – mechanical agitation) (Source: Das and Nandi, 2020)

electrode reduces the maintenance required during current reversal, particularly compared to cylinder electrochemical devices. The main disadvantage of such cell shape is mixing, but it is nonetheless regarded as the most adaptable design in terms of flow rate (Fig. 5b).

The arrangement and spacing of the electrodes, together with the reactor's operational volume, determine the electrode area-to-volume ratio (A/V). While the electrochemical geometry additionally affects the performance of EC.

When scaling up the designs of electrochemical plants from the laboratory to the full-scale equipment, it is crucial to maintain the electrode area-to-volume (A/V) ratio in order to preserve identical inter-electrode spacing with electrode plates. This ratio usually falls between 15 $m^2/m^3$ and 45 $m^2/m^3$. An increase in the A/V ratio results in shorter therapy durations and lower optimal current densities. Once the electrode area is sufficiently large, the current-to-volume (I/V) ratio becomes the main parameter influencing the system's performance.

The integration of current density with the electrode area-to-volume ratio facilitates the use of the equation (29) in batch settings to determine the amount of coagulating agents released into water for a specified treated duration. The reactor capacity in a continuous system dictates the residence period for a given water/wastewater flow rate, enabling the computation of coagulant dosage.

$$C = \frac{M}{ZF}\left(\frac{I}{V}\right) \cdot T \tag{6}$$

Where c and v represent the EC device working volume ($m^3$) and the assumed amount of metallic cations ($g/m^3$), respectively. Other than a non-traditionally shaped electrochemically-driven airlift reactor, standard reactor geometries such as a cylinder, a cubic, and rectangle parallelepiped have a minimal impact on electrochemical efficiency.

There has been research on multiple aspects of the design of electrochemical reactors to increase the efficiency of the wastewater treatment. Figure 6 illustrates various reactor designs. The electrochemical treatment process utilizing vertical and horizontal electrode designs have been compared with respect to their effectiveness in separating oil and grease (Kobya and Demirbas, 2015).

The anode cell contained an array of separated horizontal Al cylinders. The tendency for anode passivation decreased as the mass transfer towards the anode increased in the horizontal cell. This design is more efficient than the conventional vertical parallel-plate design due to its higher throughput. The efficacy of rotating cylindrical electrodes in the electrochemical demulsification process of crude oil emulsions was also investigated (Demirci et al., 2015). In the EC process with rotating electrodes, the efficiency of anode passivation may be reduced while enhancing the mass transfer of the solution to the anode. The turbulence of the rotating anode also favourably mixes the bulk solution, further increasing treatment efficiency. This is because the separation of oil and grease in an electrochemical cell can also occur using high porosity fixed-bed sacrificial anodes. The latter offers many benefits to a typical electrode configuration (horizontal or vertical anodes), including small footprint, high removal rates, and longer periods of treatment between electrode replacement. The use of an Al wire gauze anode also raised interest in the separation of crude oil emulsions in an electrochemical cell (Freitas and Valente, 2015; Fouad et al., 2009). A different type of reactor for treating the oil-in-water emulsions uses dimensionally stable anodes (electrodes) that utilise electrochemical oxidation for separation, whereas EC technology is different.

Additionally, considering the dynamics in EC technology industry, notable technological progress has been observed in recent years to improve the control of the process parameters during operation. When separating an oil emulsion using EC technology, the impact of pulse electric voltage on energy consumption was investigated. It is clear that it is beneficial to avoid the excessive energy consumption with the aid of pulse electric voltage during operation for EC technology. According to the investigation, a high level of energy saving (48%) is achieved in continuous operation mode with high efficiency.

It was determined that cavitation bubbles could be easily disrupted or induced to coalesce during the sonication process. This also considerably reduced the formation of floc particles. Therefore, it was concluded that continuous sonication is typically not suitable for the EC process. However, modifying the method of control during EC processing to include periodic sonication can effectively reduce the passivation problems. Reactor configurations, such as high-porosity fixed-bed, rotating cylinder, vertical, and horizontal plate reactors, have been receiving increased attention recently for removing contaminant from wastewater. Many factors determine the operation these reactors, such as electrode material, mode of operation (batch mode vs continuous mode), power source, depth-width ratio, total effective area, and volume. Therefore, optimising these factors is necessary for higher treatment performance of the EC process.

Moreover, during EC treatment using direct electric current, electrode passivation in direct electric mode can cause the blocking of activated sites on the electrode's surface, thereby restricting the efficiency of EC treatment. However, making use of alternate electric power sources with pulse electric fields, on the other hand, prevents this issue.

## EFFECT OF WATER CONDUCTIVITY

The conductivity and ionic strength of wastewater or water substantially affects the efficacy of current density. With the rise in electrolytic conductivity, the Ohmic resistance of water and wastewater drops, improving the current density efficiency. The duration of treatment required to attain a particular removal yield is also reduced by conductivity (Halpegama et al., 2021). Consequently, the energy usage decreases. Electrolytic conductivity is often increased by using NaCl.

Additionally, chloride anions play a crucial role in preventing calcium carbonate build-up on electrodes and assist in water treatment through oxidation processes. A concentration is recommended for effective wastewater processing (Nidheesh et al., 2022).

Nonetheless, the enhancement of conductivity is limited in wastewater treatment, particularly in the purification of drinking water. Wastewater treatment standards must be adhered to, depending on whether the treated wastewater is going to be released into the environment or reused. Along with the secondary contaminants that may arise from elevated conductivity. The regulatory standards stipulate a maximum chloride content of 250 mg/l in industrial effluents, indicating the fact that the conductivity rise following drinking water treatment by EC is notably constrained (Koul et al., 2022). Furthermore, previous works that have highlighted the significance of direct influence of electrical conductivity on coagulant species and floc formation during electrocoagulation (Moussa et al., 2017; Mollah et al., 2004). A higher ionic strength increases the efficiency of charge neutralization and aggregation; hence, the rate of removal of pollutants at lower energy costs (Jafari et al., 2023). On the other hand, sodium chloride not only increases conductivity levels and is responsible for producing chloride radicals that take active parts in anode oxidation reactions, forming reactive chlorine species (RCS). These includ hypochlorous acid (HoCl) and hypochlorite ion ($OCl^-$), which support the oxidation of organic materials (Berrera-Diaz et al., 2018).

However, higher chloride concentrations may cause several negative secondary effects, such as electrode corrosion , increased secondary pollution, and the formation of toxic chlorinated by-products (Bazrafshan et al., 2015). Therefore, while a higher level of conductivity can enhance the performance of EC technology, a safe level of chloride needs to be ensured for discharge requirements (Mollah et al., 2004).

## EFFECT OF TEMPERATURE

Temperature significantly affects the efficiency with which the EC process removes pollutants. Given that temperature can influence the electrochemical coagulation process, both positively and negatively, it is essential to understand the elements that cause temperature variations during an EC process conducted at ambient temperature. The efficacy of pollution removal diminishes as the temperature increases due to the lower formation of metal hydroxide. The decreased anodic dissolution rate at reduced temperatures results in lower pollutant removal effectiveness. Temperature affects the electrocoagulation process by modifying the kinetics of gas bubbles, reaction rates, absorption of the metal hydroxides, and liquid conductance. The effect of temperature (20–50°C) on phosphate elimination from wastewater using aluminium electrodes indicated that higher temperatures improve the removal efficiency by promoting the formation of aluminium hydroxides and increasing the mass transference of aluminium ions from the anode surface to the bulk solution. Elevating temperatures over 50°C is not advisable, as this reduces efficiency and modifies the rate of reaction and its efficacy. Further recent evidence supports the complex effects of temperature on EC performance. Higher temperatures invariably increase the performance of electrochemical reactions and electrolyte conductivity, resulting in decreased the cell voltage and energy consumption. However an increase in temperature can cause flocs to become unstable due to reduced polymeric metal hydroxides and accelerated decomposition of coagulant materials (Syam Babu et al., 2020; Kobya et al., 2020).

At a medium temperature range of 25–40°C, international studies have found that higher removal of pollutants was achieved due to better mass transfer characteristics and bubble dynamics, which increase the collision of particles and the efficiency of flotation processes (Bazrafshan et al., 2015). In international experiments carried out on wastewater with dye contaminants and oily wastewater, higher temperatures from 25°C to 40°C increased the efficiency of colour and COD removal by 10–20%, while further temperature increases beyond 50°C reduced efficiencies due to lower stability of coagulant and bubble coalescence (Zhang et al., 2023).

The solubility and precipitation properties of metal hydroxides are also affected by the temperature. At lower temperatures, the lower solubility of aluminium and iron hydroxides can lead to higher sludge yields at lower removal rates. However, at higher temperatures, increased dissolution can result in the accumulation of amorphous or less adsorptive flocs with higher rates of dissolution (Gunduz and Atabey, 2019). Temperature effects can also impact hydrogen gas evolution at the cathode and the flotation of SS.

Therefore, a temperature range of 25–40°C is often preferred for all types of wastewater in order to optimise coagulant development and reaction kinetic rates while reducing energy costs. Temperatures that are too low or too high may impede the EC method by affecting the electrochemical environment, coagulant types, and gas evolution rates (Garcia-Espinoza et al., 2025; Demirci and Ozbeyaz, 2015)

## IMPACT OF INITIAL POLLUTANT CONCENTRATION

An important factor that affects the performance of the electrocoagulation technique for treating wastewater is the initial concentration of pollutants. It is widely accepted in the literature that a higher initial concentration of pollutants directly impact the EC by reducing its effectiveness when other factors are kept constant (Das et al., 2023). This means that higher concentrations of pollutants require more coagulant at a fixed current intensity for a specified electrolysis time, which results in a lower mass of coagulant being needed to destabilise a higher mass of pollutants. At high initial concentrations, a removal efficiency is reduced due to some problems with mechanisms because the rate of metal hydroxide coagulant production (e.g., $Al(OH)_3$ or $Fe(OH)_3$) depends on Faraday's law and the current/time. Therefore, a higher pollutant concentration at a fixed current/time results in a lower coagulant-to-pollutant ratio, leading to incomplete coagulation (Arora et al., 2018). A higher pollutant load saturates the adsorption capacity of the flocs. This leaves fewer active adsorption sites remain, resulting in an increased amount of unflocculated pollutants.. Concentrations of pollutants may also influence the ionic strength, conductivity, or viscosity of the solution, thereby changing the dynamics of mass transfer, bubble adhesion/formation processes, or floc formation (Gilpavas et al., 2020). Higher concentrations may demand longer electrolysis times and higher current densities to achieve the proper yields of removal. This further increases the energy demand per unit mass of the pollutants removed. For instance, the energy demand for electrolysis rises due to higher concentrations that may relate to higher resistances or conductivities of the cell (Arora et al., 2018).

In reality, when the initial value of the concentration of the pollutants increases with all other factors held constant (current density, type of electrodes, electrolysis time, pH), one finds that:

- A lower final removal efficiency (percentage of pollutant removed).
- A longer time required to reach the same residual concentration.
- Higher specific energy consumption (kWh/kg or per g of pollutant removed).
- Potential for less efficient floc formation, slower settlement times and possibly higher sludge yields resulting from sub-optimally dosed coagulants.

For example, in a recent study where EC was optimised for a high-loaded grey water stream, it was observed that while higher current densities and longer treatment times led to better contaminant removal, at higher contaminant concentrations, the ability to scale posed some difficulties (Khan et al., 2023).

Therefore, for design and operational reasons, initial pollutant concentration should be taken into account when designing an EC system. If it is high, the following should be considered to guide the design:

1. Current density (to produce a higher coagulant).
2. Raising the electrolysis time (for more coagulant production), modifying the electrode surface area, or spacing to optimise coagulant synthesis and contact. Pre-treatment techniques for the dilution/segregation of high load streams to facilitate the effective operation of the EC at medium loads. Monitoring and optimisation of energy utilisation in order to ensure that the unit remains economically viable with the rising loads.

## EFFECT OF ELECTROLYSIS TIME

One of the key operational factors that affect the efficiency of pollutant treatment using the electrochemical coagulation technique is electrolysis time. It simultaneously influences the amount of coagulant formed and the total cost of treating pollutants. Typically, an increase in electrolysis time results in a higher concentration of dissolved metal ions from the sacrificial anode. This leads to the formation of hydroxide flocs and improving the efficiency of pollutant treatment (Jafari et al., 2023). At a fixed current density, longer electrolysis times can be achieved for the continuous generation of metal hydroxides like $Al(OH)_3$ or $Fe(OH)_3$, which proactively adsorb, destabilise, and coagulate suspended and soluble pollutants (Sahu et al., 2014; Eryuruk et al., 2018). But, after a certain optimum electrolysis time, an additional electrolysis time does not help the effective removal of pollutants, as an adequate amount of coagulant and flocs are already produced to obtain the maximum level of treatment efficiency (Bazrafshan et al., 2015). An increased electrolysis time can also exceed the re-dissolution of flocs or the destabilisation of colloidal particles with reduced treatment efficiency (Al-Raad and Hanafiah, 2021).

Furthermore, a long electrolysis time affects the economy of the treatment process. A longer electrolysis time consumes higher amounts of energy and electrolyte, generating higher amounts of secondary sludge and costing more to operate EC technology (Barrera-Diaz et al., 2018). Optimum electrolysis times, at which a balance can be achieved between the efficiency of metal ion removal and lower electrolyte consumption have been found to be necessary in order to obtain high levels of treatment performance and the economic sustainability of the method (Kobya et al., 2020). Typically, the range of optimum electrolysis times may differ depending on the wastewater characteristics and current densities applied. For instance, according to Moussa et al. (2017), industrial and municipal wastewater should be electrolysed for a period of 10 to 30 minutes for a maximum efficiency of contaminant removal. Exceeding this time may increase the energy input significantly without a commensurate increase in additional contaminant removal. Therefore, there should be a between electrolysis times and energy efficiency for a system to run sustainably (Moussa et al., 2017).

## DISCUSSION

An analysis of recent subject literature proves that electrocoagulation (EC) is a versatile, flexible, and economical technique for treating wastewater. The removal efficiencies in excess of 80% have been recorded for COD, BOD, colour, and turbidity in various types of effluents, including those from textile and leather industries, as well as hospital, municipal, and other industrial sectors, under optimised settings. These results are compiled in Table 2, and substantiate the effectiveness of electrocoagulation (Bayramoglu et al., 2004). Optimised process conditions for efficient removal, in general, include pH values between 5 and 7, a value of 10–30 mA/cm² for current density, and an interelectrode distances in the range of 0.5–1.0 cm (Syam Babu et al., 2020; Rahman et al., 2024).

The type of electrodes used has a significant influence on the EC process. Aluminium and iron electrodes continue to be the most widely used due to their abundance, low cost, and ability to effectively remove electrolytic charge through the deposition of amorphous hydroxide layer (Syam Babu et al., 2020). The use of aluminium electrodes, for instance, has several advantages, including the ability to inhibit water colouring, the formation of lighter flocs, and greater floc stability, despite the limited reaction rate. In contrast, iron electrodes cause water to exhibit a red-brown tint when released from the system (Rahman et al., 2024). Other alternatives include using electrodes made from materials such as copper, zinc, magnesium, and manganese. These alternatives are recommended for oils and dyes, respectively, and are less expensive, albeit more susceptible to corrosion (Barrera-Diaz et al., 2018). Additionally, recent experimental research has also focused on modifying electrodes (composite electrodes) such as Al–$TiO_2$ and Fe-Graphite, supported on a carbon structure, that demonstrate better stability and lower passivation rates than traditional metal-based electrodes (Zainul et al., 2024).

Operational factors, such as conductivity, pH, and current density, play major roles in the extent of pollutant removal. Increasing the current density improves the rate of anodic dissolution and bubble formation, thereby enhancing the removal efficiency to a certain level, beyond which excess current leads to undesirable side reactions, causing the electrodes to wear out. For example, Rahman et al. (2024) recorded 98.5% COD removal at a current density of 2.5 $mA/cm^2$, while Bener et al. (2019) found that maximum TOC removal for textile effluent sample was at 100 $mA/cm^2$. Meanwhile, palm oil mill effluent obtained 96% COD and 94% BOD removal level using the same range of current density, thereby proving that optimising the value of current density raises the coagulant production rate and enhances floc productivity (Zhang et al., 2021). The level of pH also plays vital role – close to neutral pH values are ideal for $Fe(OH)_3$ and $Al(OH)_3$, having highest adsorption and charge neutralisation properties, thereby acting as better adsorbents (Ebba et al., 2022). At pH values greater than 9, the substances form soluble compounds like $Fe(OH)_4^-$ and $Al(OH)_4^-$, leading to poor coagulant activity, whereas low pH increases the electrolytic counterpart, concomitantly raising the energy costs (Hossain et al., 2013). Moreover, the study by (Ozyonar, 2016) clearly reveals that maximum removal for both Al–Al and Fe–Fe electrodes was obtained at pH values of 7.5 and 6.5, respectively. It demonstrates that levels close to neutrality give better coagulant-electrochemical activity interaction.

The value of inter-electrode distances translate to the strength of the electric field, the size of coagulant doses, and ohmic resistances in the EC process. Smaller distances (0.5–1.0 cm) are characterised by greater removal efficiencies, facilitating better ion migration and lower energy requirements (Syam Babu et al., 2020; Bayramoglu et al., 2004; Akarsu et al., 2016). Akarsu et al. (2016) found that increasing distances from 1 cm to 8 cm decreased COD removal from 89.9% to 52%, whereas Rahman et al. report turbidity at 93.7% and TOC removal at 85.5% ,at a distance of 0.5 cm. The results clearly indicate that optimised distances can significantly improve the migration rates of charges and coagulant distribution, especially for highly polluted wastewaters. Other important factors related to the reactor configuration also make a substantial contribution to scaling up and optimising the effectiveness and energy requirements of each type of electrical coagulation process. Vertical, horizontal, and plate reactors are used mainly because they are easy to configure. However, cylinder, airlift, and pulse current reactors can significantly improve turbulence, passivation, and energy requirements – up to 40–50%. The reactors that utilise sonic conditions, along with alternating electric fields, considerably improved the extent of decolorisation, oil removal, and sludge recovery rates in electrical coagulation reactors. Conductivity and temperature are secondary, yet important, factors affecting the efficiency of EC. Increasing ionic strength using NaCl helps lower the electrical resistance of the solution and increases the production of oxidising chlorine species, which can oxidise organic compounds. However, it has been observed that higher chloride levels ($> 250\ mg \cdot l^{-1}$) can lead to the corrosion of electrodes, thereby forming toxic chloro-derived by-products that contaminate the treated effluent and compromise its safety. Thus, achieving the correct level of conductivity is critical for effective contaminant removal without reducing the system's longevity. Factors affecting the process kinetically include temperature, especially in relation to reaction rates, gas bubble accumulation, and coagulant solubility. Research has also proposed that temperatures around 25–40°C can improve contaminant removal efficiency, favouring greater ion mobility and gas bubble coalescence. However, higher temperatures (> 50°C) can lead to unstable hydroxide flocs, albeit with diminishing adsorption ability (Zainul et al., 2024). Overall the subject literature reveals that the EC can remove over 90 % of COD and colour from textile, leather, and refinery effluents, over 85% of BOD and turbidity from municipal and domestic wastes, and over 95 % of heavy metals and fluoride from various industrial effluents (Bayramoglu et al., 2004). Recent studies on the removal of novel contaminants, such as microplastics and titanic dioxide nanoparticles, using EC have exhibited efficiency rates exceeding 90%, demonstrating the ability of EC to remove resistant materials (Gilpavas et al., 2020). The energy consumed by the process has ranged from 0.5 to 5 kWh/m$^3$, depending on the type of effluent, design adopted, and the level of process synchrony (Zhang et al., 2021). Combining EC with biological degradation, photocatalysis, and membrane filtration has led to synergies, achieving better total removal efficiency and variances in sludge characteristics (Gilpavas et al., 2020). The results indicate that EC is a technologically developed, environmentally acceptable, and economically feasible technique for treating various complex effluents. Anti-passivation electrodes, energy-saving reactors, standardisation of the pilot-scale technique and life-cycle cost analysis studies are expected in future research in order to facilitate widespread adoption of this technique for the sustainable management of waste (Zainul et al., 2024).

## CONCLUSION

The electrocoagulation process has been identified as the most versatile, efficient, and environmentally sound technique for treating wastewater. The findings and discussions within the context of the present review have confirmed the high capability of the EC treatment technique to remove different types of contaminants from wastewater, including heavy metals, dyes, organic matter, suspended solids, nutrients, as well as novel pollutants, such as pharmaceutical compounds, microplastics, and fluorides. The high flexibility of the process stems from its integrated combination of various mechanisms, such as electrochemical oxidation, coagulation, flotation, and adsorption.

The data has proved that the electrode material, pH value, current density, and inter-electrode distance were the most important factors that affect the performance of the electrocoagulation system. As mentioned above, aluminium and iron electrodes are now still the most commonly used electrodes due to the high availability of these metals and their high coagulation power. Both types of electrodes form amorphous metal hydroxides that remove the charges of particles and facilitate flocculation. In comparison to iron electrodes, aluminium electrodes produce lighter and more transparent effluents. However, Fe electrodes create sludge at higher reaction rates, but with a higher reaction mass. Data shows that the hybrid/metallic modified electrodes have attracted more attention in recent years due to the increased reaction stability, prevention of electrode passivation, and higher sustainability.

Operational factors also retain an equal level of significance with regard to system efficiency. Higher current density promotes both anodic oxidation and bubble evolution. As such, higher pollutant removal efficiency can be realised up to an optimum level. However, input current above the optimum level contributes to increased energy expenditure. Current density levels of 10–30 mA/cm$^2$ and a pH of 5–7 remain ideal for most effluents. Consequently, both coagulation efficiency and the prevention of reaction mechanisms prove effective. The distance between the electrodes plays an important role in ensuring that the electric field and ion movement levels stay optimised. As a result, shorter electrodes of 0.5–1.0 cm achieve higher efficiency and power consumption. Solution conductivity and temperature has an important role in solution ion migration and coagulant solubility. Therefore, moderate solution conductivity levels, which can be realised by adding NaCl, are important. Temperatures within 25–40°C demonstrate their significance in coagulant particle suspension.

The paper also emphasises the role of reactor design and hydrodynamics. The most commonly employed laboratory reactor designs include batch-type and vertical plate-type reactors. However, new designs such as the rotating cylinder-type reactor, the tubular flow reactor, the airlift reactor, and the rotating tubular reactor have been developed. These new designs have improved mass transfer efficiency, resulting in uniform dispersal of the coagulant. Electrode passivation has been minimised with the advent of new designs, such as the pulse power reactor and the sono-electrocoagulation. These designs have huge potential in industrial wastewater treatment techniques. They offer a great advantage of saving of 40–50% energy compared to conventional coagulation.

Another important advantage of electrocoagulation techniques is their ease of operation and eco-friendliness. Unlike chemical coagulation processes, which require constant addition of chemicals, electrocoagulation processes only require chemicals to be added once. As such, the amount of sludge produced by the former processes tends to be higher compared to the latter ones. The sludge produced in the electrocoagulation process tends to be more resistant and less hydrated. In addition, there may be limited secondary pollution and the use of automatic control systems. The technique can also function well using solar power. Despite these benefits, some challenges need to be overcome to ensure widespread use of the EC process. These challenges include corrosion and scaling of the electrodes, high power consumption at low electrolyte conductivity, and the problem of continuous removal of sludge in long-term applications. Addressing these challenges demands specific research into the design of anti-passivation electrodes and on the integration of the EC process with suitable technologies. For instance, integrating the process with advanced oxidation processes (AOP), photocatalysis, membrane processes or biological treatment has led to synergetic benefits in pollutant treatment and nutrient reuse. The kinetic analysis of EC reaction mechanisms should also be an area of future research to predict pollutants behaviour . The absence of a standardised testing protocol makes it difficult to compare the findings of various studies. The life cycle assessment of the overall environmental and economic viability of an EC plant should considered be an important area of research. The laboratory findings should be confirmed by pilot plants using real wastewater sources. The process should then be modified for industrial implementation. In summary, electrocoagulation is a promising and dynamic treatment technique, with great potential to transform the existing wastewater treatment practices. Electrocoagulation may undergo further enhancements to the electrode design and hybrid processing in order to increase efficiency levels and decrease overall energy input as well as sludge production. With the proper optimisation and support of various industry stakeholders, the electrocoagulation treatment technique has tremendous potential to address successfully the global agendas of water reuse and resource recovery as well as environmental protection.

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## KRYTYCZNY PRZEGLĄD MATERIAŁÓW ELEKTRODOWYCH, MECHANIZMÓW REAKCJI I KONSTRUKCJI REAKTORÓW WYKORZYSTYWANYCH W ELEKTROKOAGULACJI PODCZAS OCZYSZCZANIA ŚCIEKÓW

### ABSTRAKT

**Cel badań**

Elektrokoagulacja (EC) to szeroko stosowana technika oczyszczania ścieków, która została dokładnie zbadana pod kątem szeregu zanieczyszczeń występujących w ściekach. Celem niniejszego artykułu jest przegląd elektrokoagulacji (EC) jako metody oczyszczania ścieków.

**Materiały i metody**

W artykule podsumowano i omówiono najnowsze rozwiązania w zakresie geometrii reaktorów i ich skalowania, materiałów elektrodowych i ich modyfikacji, mechanizmów reakcji i kinetyki, a także parametrów operacyjnych (gęstość prądu, pH, przewodność, odległość między elektrodami, temperatura). Przedstawiony przegląd obejmuje sprzężone, hybrydowe systemy oparte na EC, zapewniając porównanie wydajności w zależności od rodzaju ścieków oraz ocenę czynników technologiczno-ekonomicznych i środowiskowych, mających wpływ na ich wdrażanie.

**Wyniki i wnioski**

Przegląd pozwala na sformułowanie następujących wniosków: 1) elektrody na bazie żelaza i aluminium pozostają dominujące, jednak elektrody niemetalowe i modyfikowane wykazują potencjał w zakresie poprawy selektywności i zmniejszenia pasywacji; 2) do podstawowych mechanizmów usuwania zalicza się anodowe elektrolityczne rozpuszczanie, a następnie hydrolizę i adsorpcję/flokulację wymiatającą, przy czym zachowanie kinetyczne zmienia się w zależności od kategorii zanieczyszczeń i trybu pracy reaktora; 3) konstrukcja reaktora (stosunek A/V, geometria elektrod, reżim przepływu) wywiera wyraźny wpływ na transfer masy, zużycie energii i potencjał skalowania; 4) praktyczne ograniczenia obejmują pasywację elektrod, zużycie energii i gospodarkę osadami.

**Słowa kluczowe:** elektrokoagulacja, oczyszczanie ścieków, elektrody, konstrukcja reaktora, mechanizm reakcji