Acadlore Transactions on Geosciences
https://www.acadlore.com/journals/ATG

Exploring the Potential and Challenges of Electrochemical Processes for Sustainable Waste Water Remediation and Treatment

Olusola D. Ogundele*, David A. Oyegoke, Temitope E. Anaun

Department of Chemical Sciences, Achievers University, 341107 Owo, Ondo State, Nigeria

* Correspondence: Olusola D. Ogundele (olusoladavidogundele@gmail.com)

Received: 05-10-2023 **Revised:** 06-02-2023 **Accepted:** 06-13-2023

Citation: O. D. Ogundele, D. A. Oyegoke, and T. E. Anaun, "Exploring the potential and challenges of electrochemical processes for sustainable waste water remediation and treatment," *Acadlore Trans. Geosci.*, vol. 2, no. 2, pp. 80–93, 2023. https://doi.org/10.56578/atg020203.

Abstract: Emerging as an efficient, cost-effective, and environmentally sound approach, electrochemical treatment methods hold significant promise for sustainable remediation and wastewater treatment. This review elucidates recent progress in electrochemical techniques used for site decontamination and wastewater management. It elucidates the fundamental electrochemical processes, detailing the principles of electrocoagulation, electroflocculation, electrochemical membranes, electrochemical oxidation (EO), and advanced oxidation processes (AOPs). The broad applicability of these methods for contaminant removal, inclusive of heavy metals, organic pollutants, complex organic compounds, and suspended particulate matter, is underscored. Notwithstanding, the adoption of these techniques encounters notable challenges. These involve the heterogeneity of soil conditions, the presence of intricate contaminant mixtures, and the risk of electrode fouling and degradation. Suggestions for overcoming such challenges include refining the comprehension of electrochemical treatment processes in field-scale applications, investigating innovative electrode materials, and developing advanced modeling and simulation tools. This review offers a robust overview of electrochemical treatment strategies for sustainable wastewater management and can guide researchers, engineers, and policymakers towards the successful adoption and implementation of these techniques to meet environmental challenges and foster sustainable water management.

Keywords: Electrochemical treatment; Sustainable remediation; Wastewater treatment; Heavy metal pollution; Environmental pollution

1 Introduction

A heightened sense of urgency surrounds environmental concerns linked to water resources. These concerns have been fueled by multiple factors, from hazardous substance release and nutrient pollution to microbial contamination [1]. The discharges associated with industrial activities, lacking proper control measures, combined with incorrect waste disposal methods and chemical spills, have resulted in the contamination of both soil and groundwater [1]. Such pollution forms are acknowledged as having profound impacts on both the ecology and human health. Consequently, the need for sustainable remediation techniques has been emphasized [2].

Illustrative examples of the catastrophic environmental and health impacts of water pollution have been documented in recent history. The Exxon Valdez Oil Spill of 1989 discharged approximately 260,000 to 750,000 barrels of crude oil into Prince William Sound, Alaska [3]. An estimated 1,300 miles of coastline experienced the impacts of this spill, resulting in severe damage to the ecosystem, including the death of thousands of marine birds, sea otters, fish, and other wildlife [3]. Another instance is the outbreak of waterborne diseases in Walkerton, Canada, in 2000, triggered by E. coli and Campylobacter bacteria contamination in the town's water supply [4]. The outbreak led to seven fatalities and left thousands suffering from illnesses, underscoring the importance of rigorous water treatment and monitoring systems to secure safe drinking water for communities [4]. Additionally, the contamination of the Ganges River in India by industrial effluents, sewage, and agricultural runoff carrying pesticides and fertilizers poses significant threats to aquatic life and biodiversity [5]. Manifestations of this ecological impact include the decline in several fish species and loss of habitat for Ganges river dolphins [5]. In the case of the Flint water crisis in Michigan, USA, from 2014 to 2015, an improperly managed switch in water supply caused lead to leach from aging pipes, exposing thousands of residents to lead-contaminated drinking water [6]. As a result, elevated blood lead levels in children and associated health issues such as developmental delays and cognitive impairments were observed [6].

The necessity for sustainable remediation of contaminated sites and effective wastewater treatment has been recognized as an imperative step in addressing these concerns and safeguarding the environment. Notably, industrial activities, such as manufacturing, mining, and energy production, contribute significantly to water pollution. These activities are known to generate effluents containing a wide array of pollutants, including heavy metals, organic compounds, and nutrients [7]. Without sufficient treatment or proper disposal, these industrial wastewaters can precipitate severe ecological damage and pose health risks. Consequently, the implementation of sustainable practices and the introduction of advanced treatment technologies are deemed crucial for minimizing the environmental impact of industrial activities [7].

The critical role of wastewater treatment in safeguarding public health and the environment is unequivocally acknowledged, with its primary function being the elimination of pollutants before their subsequent release into natural water bodies [8]. Standard wastewater treatment protocols typically encompass physical, chemical, and biological procedures, yet these traditional methods often necessitate substantial energy expenditure and generate considerable amounts of waste sludge. It thus becomes incumbent upon the sector to embrace innovative technologies and strategies that support sustainable wastewater treatment.

The term sustainable remediation is coined to denote a holistic approach that seeks to remediate contaminated sites whilst minimizing the environmental footprint and taking into account potential long-term repercussions [9]. Central to this approach is the integration of green and sustainable practices, including the use of renewable energy, the reduction of greenhouse gas emissions, and the optimization of resource utilization. The ultimate aim of sustainable remediation strategies is to reconcile remediation goals with environmental, social, and economic considerations, thereby leading to a more comprehensive and balanced approach [10].

In the quest for sustainable wastewater treatment and remediation, electrochemical treatment has recently gained traction as a promising technology [11]. This novel approach deploys electrochemical processes for contaminant removal, offering several distinctive advantages. The process of electrochemical treatment consists of applying an electric current to induce chemical reactions that aid in the eradication of pollutants. Key attributes of this technology encompass its versatility, efficiency, and selectivity. It can be customized to target specific contaminants, making it applicable to a diverse range of wastewater compositions. Moreover, through the choice of electrode materials with distinct properties, pollutant removal can be made selective, thereby enhancing the efficiency of treatment [12].

Several merits of electrochemical treatment over traditional wastewater treatment methods are observed. Primarily, it is energy-efficient, given that the process can be optimized to minimize energy consumption. Furthermore, the generation of significant amounts of sludge, a common issue with conventional treatment methods, is notably reduced, thereby decreasing the need for further disposal or treatment. This feature aligns with the principles of sustainable remediation by curtailing waste generation and the ensuing environmental impact. Additionally, the operation of the technology at ambient temperatures negates the necessity for supplementary energy-intensive heating or cooling processes [13].

The robust treatment performance and versatility of electrochemical treatment is reflected in its effective removal of a wide array of contaminants, inclusive of organic pollutants, heavy metals, and nutrients. The electrochemical oxidation process is proficient in the degradation of complex organic compounds, while electrocoagulation and electrodeposition processes facilitate the removal of suspended solids and heavy metals. Importantly, the technology can be paired with other treatment methods to harness synergistic effects, thereby further boosting its efficiency [14].

Given its myriad benefits, electrochemical treatment holds considerable potential for sustainable remediation and wastewater treatment. Its versatility makes it a viable option for remediation of various contaminated sites, such as industrial and agricultural areas. It is capable of treating soil and groundwater contaminated with persistent organic pollutants, heavy metals, and emerging contaminants effectively. Its capacity to specifically target contaminants and achieve high treatment efficiencies renders it an appealing alternative for environmental clean-up [15].

Emerging within the realm of wastewater treatment, electrochemical processes demonstrate a compelling capacity for pollutant removal, thereby complying with rigorous discharge regulations [15]. This technology has proven its efficacy in diverse industrial wastewater sectors, notably textiles, pharmaceuticals, and petrochemicals. Moreover, incorporation of electrochemical treatment into decentralized wastewater systems has been proposed, promising a sustainable approach to wastewater management in isolated or resource-limited locales [15].

The breadth of pollutant types addressed by electrochemical techniques, such as electrocoagulation and electrooxidation, is impressive. Organic compounds, heavy metals, and pathogens, among others, are efficiently removed through these processes [12]. The ensuing electrochemical reactions and processes actively disintegrate contaminants, facilitating their subsequent removal from wastewater. These techniques accommodate a variety of wastewater types, from industrial effluents and domestic sewage to agricultural runoff, exhibiting adaptability to diverse treatment scenarios and efficacy even in the presence of multifaceted contaminant streams [13].

From an economical perspective, electrochemical treatment methods provide significant advantages over traditional methodologies. Operating under ambient temperatures and pressures, these methods forgo energy-intensive heating or pressurization procedures. The requisite electrodes and electrochemical cells necessitate minimal maintenance and exhibit a scalability that adjusts to wastewater volume [13]. A distinct reduction in sludge production is observed in comparison with other techniques such as chemical coagulation or biological processes. This diminishes the expenditures related to sludge management and lessens the environmental toll of sludge disposal [14].

Further advantages are realized through electrochemical advanced oxidation processes (EAOPs), which produce potent oxidizing species like hydroxyl radicals. These radicals effectively degrade persistent organic pollutants and recalcitrant compounds that other methods struggle to eliminate [15].

Interestingly, electrochemical treatment introduces opportunities for resource recovery. Selective contaminant removal enables extraction of valuable elements, such as metals, and energy-rich compounds from wastewater. Such circular approaches embody principles of a circular economy, fostering efficient resource usage and minimal waste production [15].

The merits of electrochemical treatment extend beyond its primary function of pollutant removal, fostering sustainability, economic efficiency, and potential resource recovery. As research unfolds, the scope of electrochemical techniques promises further evolution and broadening applications in wastewater management.

2 Principles and Mechanism of Electrochemical Processes

The mechanism underlying electrolysis comprises the disintegration of a compound driven by an electric current transmitted through a solution. The adoption of electrolysis in wastewater treatment extends to both oxidation and reduction reactions. Reactive oxidizing species, such as hydroxyl radicals (OH•) and ozone (O_3), generated via electrolytic oxidation, perform the function of pollutant elimination, disassembling organic pollutants into less detrimental compounds. Conversely, electrolytic reduction encompasses the reduction of pollutants via electron supply to targeted compounds, culminating in their transformation into less hazardous forms [16].

The centrality of electrode reactions within the electrochemical procedures for wastewater treatment cannot be overstated. Two electrodes, an anode, and a cathode, find immersion within the wastewater during electrolysis. Oxidation reactions transpire at the anode, triggering the release of electrons. Resistance to harsh conditions and corrosion is an imperative attribute of anode materials, and materials founded on titanium, such as titanium mesh or titanium-coated substrates, fulfill this criterion. Their chemical stability and elevated electrocatalytic activity render them suitable choices [17].

Reduction reactions, on the other hand, transpire at the cathode, where electron consumption occurs. Cathode materials, besides exhibiting superior electrical conductivity, should be selective in the reduction of the target pollutants. A range of materials, from stainless steel and carbon-based substrates (like graphite, activated carbon) to noble metals (like platinum, gold), is frequently employed as cathodes. The electrode potentials of both anode and cathode form critical parameters dictating the efficiency and selectivity of the electrochemical process. The electrode potential is a representation of an electrode's propensity to either gain or lose electrons during a redox reaction. Greater positive potential indicates an increased tendency for oxidation of species, while a more negative potential tends to favor reduction reactions [18].

In the realm of electrochemical wastewater treatment processes, redox reactions command a vital role. Oxidation reactions occur at the anode, whereby pollutants undergo oxidation via the production of reactive species like hydroxyl radicals (OH•) or chlorine (Cl_2). Reduction reactions transpire at the cathode, transforming target pollutants into less hazardous forms. These redox reactions involve an electron exchange between the electrode and the pollutants, enabling the conversion of contaminants into lower toxicity products or even complete mineralization [19]. Figure 1 illustrate an electrochemical process.

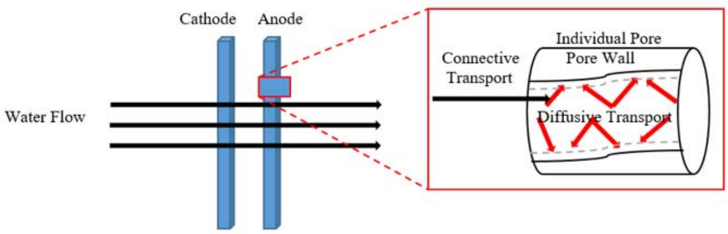

Figure 1. Schematic representation of an electrochemical process

Numerous factors, including the selection of electrode material, the applied potential, pollutant concentration, and the pH of the wastewater, impact the efficiency of electrochemical processes in wastewater treatment. The electrode material selection bears significant influence on the electrocatalytic activity and stability of the electrodes.

Optimizing the applied potential is critical to achieve the sought level of pollutant removal without excessive energy expenditure [19].

2.1 Electrochemical Cells and Reactors Used for Treatment

Electrochemical cells and reactors serve as vital components in the electrochemical systems deployed for wastewater treatment, employing electrochemical processes to proficiently remove pollutants from wastewater [19]. Among the simplest types of electrochemical cells utilized in wastewater treatment are batch systems. In these systems, a fixed volume of wastewater undergoes treatment at a time. The initiation of electrochemical reactions is brought about by the application of a direct current to electrodes immersed in the wastewater. Such systems' simplicity and ease of operation make them apt for small-scale applications or scenarios where a continuous flow of wastewater is not feasible [20].

Contrarily, continuous systems are tailored to process wastewater without interruption, and find common use in larger-scale wastewater treatment facilities. Offering advantages such as the capability to manage a high volume of wastewater, and the potential for automation and remote monitoring, wastewater is allowed to flow through the reactor in these systems. The placement of electrodes facilitates efficient pollutant removal [21].

Different configurations of electrochemical cells and reactors are adopted to boost treatment efficiency and optimize pollutant removal. A popular configuration, the flow-through system, allows wastewater to pass through the reactor unidirectionally. This setup ensures efficient mass transfer and minimizes the accumulation of byproducts, making it suitable for treating wastewater with low pollutant concentrations or when the rate of pollutant removal must be maximized [22] (Figure 2).

Another widely implemented setup in electrochemical wastewater treatment is the divided cell configuration. In this configuration, a physical barrier such as a diaphragm or ion exchange membrane separates the anode and cathode compartments. This arrangement inhibits the mixing of reaction products and enables selective treatment, minimizing electrode fouling and enhancing the overall system efficiency. Divided cells are commonly used when distinct electrochemical reactions must occur independently [21].

Membrane-assisted systems integrate the benefits of electrochemical treatment with membrane filtration. In these systems, a membrane incorporated into the electrochemical reactor separates the treated water from the electrode compartments. The membrane serves as a physical barrier, preventing the migration of contaminants and enabling selective pollutant removal. These systems prove effective in treating wastewater with complex matrices or when the separation of pollutants from treated water is paramount [23].

Each type of electrochemical cell or reactor presents its advantages and limitations. The choice of system relies on the specific composition of the wastewater, treatment objectives, and operational considerations. Factors such as energy efficiency, treatment efficiency, electrode material, and maintenance requirements should be thoroughly evaluated to select the most suitable system [23].

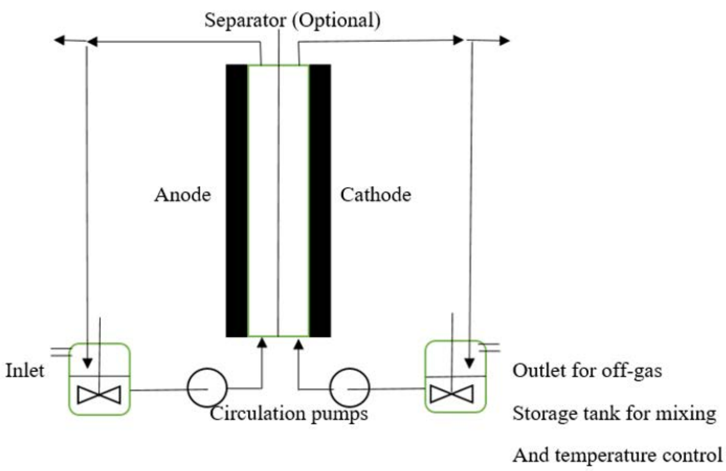

Figure 2. Illustration of an electrochemical reactor

2.2 Electrode Material and Their Roles in Wastewater Treatment Process

The indispensable role of electrode materials in electrochemical wastewater treatment processes has been underscored in recent literature [1–5]. The choice of electrode material is known to considerably influence the efficiency, selectivity, and robustness of the system [6, 7].

The first category of widely used electrode materials encompasses carbon-based compounds, such as graphite, activated carbon, and carbon nanotubes. Owing to their excellent electrical conductivity, chemical stability, and vast surface area, these materials are found to be conducive for electrochemical reactions [8, 9]. It is observed that carbon electrodes facilitate both oxidation and reduction reactions, enabling the removal of an array of pollutants. The effectiveness of these electrodes is particularly notable in the treatment of organic contaminants and heavy metals [16].

The second class of electrode materials entails metal oxides, including titanium dioxide ($\mathrm{TiO_2}$), ruthenium dioxide ($\mathrm{RuO_2}$), and iridium oxide ($\mathrm{IrO_2}$), which exhibit notable electrocatalytic activity and stability [10, 11]. These metal oxide electrodes are frequently utilized for oxygen evolution reactions at the anode, subsequently generating reactive species for pollutant oxidation. They have demonstrated remarkable efficiency in organic contaminant removal and wastewater disinfection [24].

The choice of electrode material is therefore of considerable importance, and more investigation is required to fully understand the optimal materials for different wastewater treatment contexts.

2.3 Electrode Surface Modification Techniques

Electrode surface modification techniques play an indispensable role in enhancing the performance of electrode materials in wastewater treatment, an assertion substantiated by a range of innovative strategies and their subsequent experimental validation. Diverse techniques bolster catalytic activity, augment the surface area, and optimise charge transfer kinetics, thereby promoting overall efficiency [25].

Primarily, electrode surface modification has been executed through the deposition of metal catalysts. This technique benefits from the incorporation of noble metals such as platinum (Pt) and palladium (Pd). As potent catalysts, these metals foster pollutant oxidation or reduction, thus catalysing an improvement in treatment efficiency [25].

Similarly, the application of conductive polymers to electrode surfaces represents another prevalent technique. Polyaniline and polypyrrole, known for their noteworthy electrical conductivity, are the polymers of choice. A consequent enlargement of the active surface area of the electrode is observed, along with an enhancement in pollutant adsorption and facilitation of charge transfer during the electrochemical reactions [26].

In addition to these, nanostructuring electrode materials is recognised as an effective approach to ameliorate performance. The high surface-to-volume ratio of nanostructured electrodes provides an increased number of active sites for pollutant removal. Nanomaterials of various types, encompassing nanotubes, nanowires, and nanoparticles, are integrated into the electrode structure. The small dimensions of these materials expedite mass transfer and optimise reactivity, hence boosting treatment efficiency [27].

Cutting-edge materials, such as graphene and metal-organic frameworks (MOFs), are gaining prominence in electrode surface modifications. The unique two-dimensional structure and exceptional electrical properties of graphene can enhance electrocatalytic activity and stability. MOFs, with their high porosity and customisable functionality, facilitate targeted pollutant adsorption and removal [28].

In wastewater treatment, metal-based catalysts, notably Pt, Pd, and iridium (Ir), have been utilised extensively for electrode surface modifications to augment the oxidation of organic pollutants. It has been observed that Pt-modified electrodes significantly increase the removal efficiency of refractory organic pollutants in industrial wastewater [23].

Graphene oxide-modified electrodes have also been studied for their potential to improve pollutant removal. Their vast surface area and superior electron transfer properties contribute to an enhanced removal of dye pollutants from wastewater [23].

Composite electrodes combining different materials have also been applied in wastewater treatment. A notable case is the utilisation of a composite electrode comprising carbon nanotubes and titanium dioxide ($\mathrm{CNT/TiO_2}$) for the electrochemical degradation of pharmaceutical compounds. These modified electrodes showcased a marked improvement in removal efficiency compared to conventional ones [23].

The issue of fouling in electrochemical systems is mitigated by applying electrode surface coatings. For instance, a titanium dioxide ($\mathrm{TiO_2}$) nanotube coating on titanium electrodes has been shown to significantly reduce fouling caused by organic pollutants, resulting in prolonged electrode stability and enhanced wastewater treatment performance.

These examples underscore the real-world applicability of electrode surface modification techniques in wastewater treatment scenarios. These techniques, by optimising catalytic activity, selectivity, and stability, facilitate a more efficient removal of organic pollutants, heavy metals, and other contaminants. As such, they contribute to the advancement of the field of electrochemical wastewater treatment.

3 Key Parameters Influencing the Performance of Electrochemical Treatment

The efficiency and effectiveness of electrochemical wastewater treatment hinge on numerous key parameters. A comprehensive understanding and apt optimization of these parameters are vital for high-yield pollutant removal.

3.1 Current Density

Current density, embodying the quantity of electric current distributed per electrode surface unit, crucially steers the pace of electrochemical reactions in wastewater treatment. An escalation in current densities typically translates to a rise in pollutant removal rates. Nevertheless, a surge in energy consumption and the deterioration of the electrode may result from excessively high current densities. As such, the challenge lies in determining an appropriate current density that strikes a balance between treatment efficiency and operational costs [26].

3.2 Potential

The potential imposed on the electrodes is an additional vital parameter. It regulates the driving force for the electrochemical reactions. In oxidation reactions, an increased potential expedites the creation of reactive oxidizing species, such as hydroxyl radicals or ozone, fostering efficient pollutant removal. On the contrary, a diminished potential promotes the electron supply to the targeted pollutants in reduction reactions, thereby converting them to less harmful forms. The optimization of potential is thus integral for maximizing treatment efficiency while minimizing energy consumption [28].

3.3 Residence Time

Residence time, which denotes the duration wastewater stays in contact with the electrodes, significantly influences the electrochemical treatment process. Longer residence times allow for more thorough degradation and removal of pollutants. Variables like flow rate, reactor design, and electrode configuration shape the residence time. It is crucial to balance the residence time with the desired treatment objectives to ensure optimal performance [29].

3.4 pH

The pH of the wastewater carries significant weight in the electrochemical treatment process due to its impact on pollutant speciation, the stability of electrode materials, and the generation of reactive species. For instance, in the presence of chloride ions, a lower pH favors the production of chlorine species, augmenting the oxidation of pollutants. Conversely, a high pH fosters the generation of hydroxyl radicals. Adjusting the pH accordingly can optimize treatment efficiency and specifically target pollutants [30].

3.5 Temperature

The temperature governs the reaction kinetics and mass transfer processes in electrochemical treatment. Higher temperatures generally speed up the electrochemical reactions, boosting pollutant removal rates. The solubility of gases and the wastewater's conductivity, which can further influence treatment efficiency, are also affected by temperature. However, a rise in temperature may increase energy consumption. As such, the temperature must be balanced against treatment goals and operational costs [31].

3.6 Conductivity

Conductivity, a parameter reflecting the wastewater's capacity to conduct electric current, hinges on the concentration of ions and dissolved solids in the wastewater. Increased conductivity enhances the charge transport between the electrodes, leading to improved treatment efficiency. However, exceedingly high conductivity may lead to higher energy consumption and electrode fouling. Thus, it is crucial to consider and optimize the wastewater's conductivity to achieve efficient and cost-effective treatment [32].

4 Remediation Applications of Electrochemical Treatment

Groundwater and soil contamination remediation frequently employ electrochemical treatment techniques due to their high treatment efficiency, selective pollutant removal, and minimization of secondary waste production. These techniques encompass electrocoagulation and electroflocculation processes, which are integral in wastewater treatment, as they induce the in-situ generation of coagulants or flocculants by applying electrical current. These coagulants aid in suspended solids and colloidal matter removal from wastewater. A comprehensive understanding of these processes' mechanisms and operating conditions is essential for optimizing their efficiency and effectiveness [33].

4.1 Electrocoagulation

Electrocoagulation is a process that engenders the destabilization and coagulation of suspended particles and colloids through the generation of metal ions at the anode. Typically, these metal ions are aluminum or iron. They are released into the wastewater, forming hydroxide flocs that adsorb and enmesh the particles, leading to their precipitation or agglomeration. The coagulation mechanism is primarily ascribed to charge neutralization and sweep flocculation, with the metal hydroxide flocs acting as coagulants [34]. In this process, sacrificial anodes such as iron (Fe) or aluminum (Al) are employed. Oxidation at these anodes releases metal ions that act as coagulants, neutralizing the charge of the suspended particles and colloids in the wastewater. For example, in the case of iron anodes: At the anode (oxidation):

$2\mathrm{Fe}_{(s)} \rightarrow 2\mathrm{Fe}^{2+}(\mathrm{aq}) + 4\mathrm{e}^{-}$

The released Fe^{2+} ions, for instance, undergo hydrolysis to form $\mathrm{Fe(OH)}_2$, which further reacts to form $\mathrm{Fe(OH)}_3$ precipitates, serving as coagulants aiding in the removal of suspended particles and colloids [34].

$2\mathrm{Fe}^{2+}{}_{(\mathrm{aq})} + 2\mathrm{OH}_{(\mathrm{aq})} \rightarrow \mathrm{Fe(OH)}_{2(\mathrm{~s})}$

$\mathrm{Fe(OH)}_{2(\mathrm{~s})} + \mathrm{OH}^{-}(\mathrm{aq}) \rightarrow \mathrm{Fe(OH)}_{3(\mathrm{~s})}$

4.2 Electrooxidation

Electrooxidation involves the use of anode materials such as boron-doped diamond (BDD) or mixed metal oxide electrodes. When a current is applied, electrochemical reactions occur at the anode surface, generating oxidizing species that can degrade organic pollutants. For example, in the case of hydroxyl radicals (·OH) generation at a BDD anode: At the anode (oxidation):

$\mathrm{H}_2\mathrm{O} \rightarrow 2\mathrm{H}^{+}(\mathrm{aq}) + 1/2\mathrm{O}_{2(\mathrm{~g})} + 2\mathrm{e}^{-}$

$2\mathrm{H}^{+}(\mathrm{aq}) + 2\mathrm{e}^{-} \rightarrow \mathrm{H}_2(\mathrm{~g})$

The generated H+ ions can react with water molecules to form hydroxyl radicals:

$\mathrm{H}^{+}(\mathrm{aq}) + \mathrm{H}_2\mathrm{O}_{(1)} \rightarrow \mathrm{OH}_{(\mathrm{aq})} + \mathrm{H}_{2(\mathrm{~g})}$

These hydroxyl radicals (·OH) are highly reactive and can initiate oxidation reactions with organic contaminants, breaking them down into simpler, less harmful compounds [34].

4.3 Electroflocculation

Electroflocculation is characterized by the deployment of an electric current which incites the release of metallic ions or electrolytic products from the electrodes. The ensuing formation of flocs, which are aggregations of both charged particles and metal hydroxides, are instrumental in the aggregation and subsequent precipitation of suspended solids and colloidal matter [35].

The efficiency of the removal of suspended solids and colloidal matter is contingent upon several operational conditions, of which current density, electrode material, pH, and reaction time are the most salient. Current density has been identified as a significant factor that determines the efficiency of the electrocoagulation and electroflocculation processes. Increased current densities are conducive to a higher generation of coagulants or flocculants, thereby amplifying removal efficiency. However, excessively high current densities may instigate undesirable side reactions, including excessive gas evolution, which can impede process efficiency [36].

During the electroflocculation process, an electric current is applied to the wastewater via suitable electrodes, composed of iron, aluminum, or graphite. The application of the current facilitates the release of ions from the electrodes into the water, culminating in the creation of charged species that interact with particles and colloids within the wastewater.

The process can be succinctly described as follows: Electrode dissolution occurs at the anode (oxidation), where iron in its solid state transforms into $\mathrm{Fe}^{2+}{}_{(\mathrm{aq})}$ and two electrons, and at the cathode (reduction), where two molecules of water and two electrons are converted into two hydroxide ions and a molecule of hydrogen gas. Following this, the process of charge neutralization and coagulation takes place. Metal cations released (e.g., Fe^{2+}) and hydroxide ions $\left(\mathrm{OH}^{-}\right)$migrate towards the negatively charged suspended particles and colloids in the wastewater. The oppositely charged species neutralize the charge on the particles, thus diminishing the repulsive forces between them. This neutralization results in the formation of larger aggregates or flocs, which can then be separated from the water through sedimentation or filtration processes [36].

The choice of electrode material is vital, as it affects the production of coagulants or flocculants. Aluminum and iron electrodes are commonly deployed due to their propensity to release metal ions in solution. Furthermore, the choice of electrode material impacts the energy consumption and the overall cost-effectiveness of the electrochemical treatment.

The pH of the wastewater plays a significant role in the electrocoagulation and electroflocculation processes. It dictates the solubility and speciation of metal ions, influencing the formation and stability of the generated flocs. Generally, the optimal pH range for coagulation and flocculation lies between 5 and 9, although this may deviate depending on the specific wastewater composition [36].

Reaction time is another crucial parameter influencing the efficiency of the electrochemical treatment. Adequate reaction time is necessary for the coagulation or flocculation process to reach completion, enabling the flocs to aggregate and settle, thereby facilitating their removal from the wastewater. The optimal reaction time may vary depending on the characteristics of the wastewater and the desired degree of solids removal [37].

In contrast to conventional chemical coagulation and flocculation methods, electrocoagulation and electroflocculation offer several advantages. They circumvent the need for the addition of chemical coagulants, thereby reducing chemical consumption and minimizing the generation of sludge. Moreover, electrochemical treatment can be easily automated and controlled, permitting real-time adjustments to optimize the process performance [37].

4.4 Electrochemical Oxidation and Advanced Oxidation Processes

Increased focus has been placed on the application of Electrochemical Oxidation (EO) and Advanced Oxidation Processes (AOPs) for the treatment of wastewater laden with organic pollutants and emergent contaminants [2]. This is largely attributed to the potency of electrochemical reactions and oxidizing agents leveraged by these techniques in the degradation and expulsion of diverse pollutants.

In the instance of EO, the implementation of an electric current is engaged to engender reactive species at the electrode surface, thus driving the degradation of organic compounds. This occurs within an electrolytic cell which comprises an anode and a cathode, separated by either a membrane or an ion exchange resin [3]. During the electrochemical process, oxidation reactions are initiated at the anode, subsequently leading to the creation of highly reactive hydroxyl radicals (·OH). These radicals exhibit a broad capability for initiating the oxidation of a multitude of organic pollutants, such as dyes, pesticides, pharmaceuticals, and industrial wastewater contaminants [28].

Electrodes of varied materials may be employed in EO, including but not limited to boron-doped diamond (BDD), platinum, titanium, and lead dioxide. Of these, BDD electrodes present a particular allure due to their high electrochemical stability and capacity to generate ·OH radicals at low potentials. The EO process can be further enhanced by applying direct current (DC) or by operating in a pulsed current mode, offering improved mass transfer and hindering electrode fouling [21]. The oxidation reaction can be generally represented as:

Organic compound $+\mathrm{H_2O} \rightarrow$ Products $+\mathrm{CO_2}$

It is important to note, however, that the specific oxidation reactions at the anode can fluctuate based on the organic contaminants in the water. To illustrate, if the organic compound is a phenol ($\mathrm{C_6H_6O}$):

$\mathrm{C_6H_6O + 6H_2O \rightarrow 6CO_2 + 12H^+ + 12e^-}$

Advanced oxidation processes (AOPs), being a subclass of EO methods, use potent oxidizing agents such as ozone ($\mathrm{O_3}$), hydrogen peroxide ($\mathrm{H_2O_2}$), and ultraviolet (UV) radiation in combination with electrochemical processes [32]. Such AOPs can significantly elevate the generation of reactive species, thereby facilitating the degradation of recalcitrant pollutants that resist conventional treatment methods.

Through various mechanisms, the degradation of organic pollutants and emerging contaminants in EO and AOPs occurs. These mechanisms encompass direct oxidation by reactive species, indirect oxidation by the oxidants generated, and adsorption onto the electrode surface. Reactive species, for example, hydroxyl radicals, assail the chemical bonds of organic pollutants, resulting in smaller fragments that can be more easily biodegraded. In addition, the oxidants generated, such as $\mathrm{O_3}$ and $\mathrm{H_2O_2}$, may interact with organic pollutants, decomposing them into simpler, less toxic compounds.

The fundamental reaction in AOPs is the interaction of hydroxyl radicals with organic compounds:

OH + Organic compound $\rightarrow$ Oxidized products

Hydroxyl radicals can be produced through various methods. For instance, when combining ozone $(\mathrm{O_3})$ and hydrogen peroxide $(\mathrm{H_2O_2})$:

$\mathrm{O_3 + H_2O_2 \rightarrow \cdot OH + O_2 + H_2O}$

Or, when combining ultraviolet (UV) and hydrogen peroxide ($\mathrm{O_3}$ and $\mathrm{H_2O_2}$):

$\mathrm{UV + H_2O_2 \rightarrow \cdot OH + H_2O}$

Electrochemical Oxidation (EO) and Advanced Oxidation Processes (AOPs) offer compelling methods for the removal of emergent contaminants, encompassing pharmaceuticals, personal care products, endocrine-disrupting compounds, and a diverse array of micropollutants. Traditional wastewater treatment techniques often fail to effectively eliminate these contaminants, allowing their persistence in the environment where they may cause harm to human health and the broader ecosystem due to their potential toxicity, even in minute concentrations [38].

EO and AOPs are not only promising in their ability to degrade and remove these emerging threats, they also come with multiple benefits that boost their appeal in wastewater treatment applications. Importantly, these processes mostly eliminate the need for the addition of chemicals. Only certain AOPs require the addition of hydrogen peroxide or ozone, both of which can be conveniently produced on-site [39].

Moreover, the capacity of EO and AOPs to handle a complex blend of pollutants removes the necessity for extensive pre-treatment steps. This ability simplifies the overall wastewater treatment process, making it more efficient and feasible. These methods have also demonstrated impressive energy efficiency, a benefit that is even more pronounced when coupled with renewable energy sources [39].

Emerging contaminants present significant threats to the safety of our water resources, and the effectiveness and advantages of EO and AOPs provide a promising path towards the resolution of these challenges. By leveraging the power of these processes, we can work towards more efficient, effective, and sustainable water treatment practices, helping to safeguard our vital water resources for future generations [39].

4.5 Electrochemical Membrane Processes

Electrochemical membrane processes have increasingly gained interest within the realm of wastewater treatment due to their noteworthy efficiency and selectivity in ion removal and desalination. The attention bestowed upon these processes stems from their provision of inventive solutions for selective ion removal and desalination, thereby significantly contributing to the sustainable treatment of wastewater [40].

Electrodialysis (ED), a membrane-dependent process, employs an electric field to facilitate ion transportation across ion-exchange membranes. The configuration comprises anion exchange membranes (AEMs) and cation exchange membranes (CEMs) that are alternately positioned between electrodes. Upon the application of direct current, cations migrate towards the cathode via the cation exchange membranes while anions migrate towards the anode through the anion exchange membranes. This differential transport capability enables the selective removal of specific ions from the wastewater stream [41]. Such process is depicted in Figure 3.

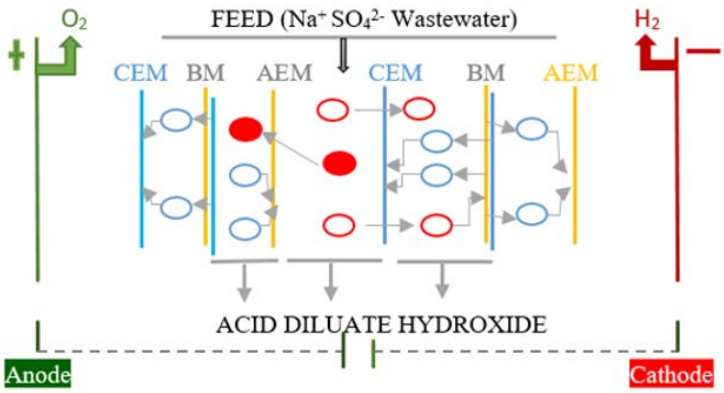

Figure 3. Schematic illustration of electrodialysis

Another prominent electrochemical membrane process is electrosorption, which relies upon the adsorption and subsequent desorption of ions on the surface of an electrically charged electrode. Porous electrode materials, such as activated carbon or ion-exchange resins, are typically used, providing a large surface area for ion adsorption [42]. Upon application of an electric potential, ions present in the wastewater are drawn to the charged electrode surface, where they become adsorbed. The adsorbed ions can then be desorbed either by reversing the electric potential or via regeneration processes [43].

In addition, electrochemical filtration, a process that integrates the principles of both electrodialysis and electrosorption, has been developed to achieve simultaneous ion removal and filtration. This method employs a stack of alternating selective ion exchange membranes and porous electrode materials [44]. Upon applying a direct current, ions are transferred across the ion exchange membranes through electrodialysis while simultaneously being adsorbed onto the electrode surface through electrosorption. This dual mechanism intensifies the overall efficiency of ion removal and filtration within a singular process [45].

Selective ion removal serves as a pivotal component of electrochemical membrane processes. By manipulating the electric potential and the membrane properties, specific ions can be selectively extracted from the wastewater stream. This selectivity proves especially beneficial in industrial wastewater treatment, where the removal of specific ions, such as heavy metals or distinct salts, is mandated. The ability to target and eliminate specific ions paves the way for tailored treatment methodologies and minimizes waste stream generation [46].

The domain of desalination also sees extensive application of electrochemical membrane processes. Given the escalating demand for freshwater resources, the removal of salts from seawater and brackish water sources is deemed vital. Processes such as electrodialysis and electrosorption can efficiently extract ions, including sodium, chloride, and other dissolved salts, from water, resulting in the production of desalinated water. These processes present a more energy-efficient and environmentally friendly alternative to conventional desalination methods, such as reverse osmosis [47].

While the aforementioned electrochemical membrane processes offer substantial benefits in terms of efficiency and selectivity, research efforts should continue in order to further optimize these processes. Moreover, attention should be devoted to exploring and developing advanced materials for ion exchange membranes and electrode materials. This would improve ion removal efficiency and expand the range of ions that can be selectively removed from wastewater, thus contributing to more sustainable and comprehensive wastewater treatment strategies.

5 Challenges and Limitation in Field-Scale Applications

Field-scale application of electrochemical treatment for wastewater encounters several challenges and limitations that need to be addressed to ensure successful implementation. Two significant challenges are the heterogeneous soil conditions and the presence of complex contaminant mixtures. These factors can impact the efficiency and effectiveness of electrochemical treatment processes [47].

Heterogeneous soil conditions present a challenge in implementing electrochemical treatment in the field. Soil heterogeneity refers to variations in soil properties, including composition, porosity, and hydraulic conductivity. These variations can influence the distribution of electric current and the transport of contaminants within the soil matrix. Uneven distribution of current can result in non-uniform treatment and incomplete degradation of pollutants. Variations in soil hydraulic conductivity can lead to preferential flow paths, which in turn may cause bypassing of contaminated zones and a reduction in treatment efficiency [48].

Complex contaminant mixtures commonly found in wastewater represent another challenge in the field-scale application of electrochemical treatment. Wastewater contains a diverse range of organic and inorganic pollutants, including heavy metals, organic compounds, pharmaceuticals, and microorganisms. The simultaneous treatment of multiple contaminants with varying chemical properties can prove challenging. The presence of one contaminant may interfere with the degradation or removal of another, thereby affecting the overall treatment efficiency. The interactions between different contaminants and their effects on electrochemical processes warrant careful consideration [49].

In addition to heterogeneous soil conditions and complex contaminant mixtures, several other factors limit the field-scale application of electrochemical treatment. One limitation is the high capital and operating costs associated with the implementation of large-scale electrochemical treatment systems [50]. The cost of constructing and maintaining the required infrastructure, including electrodes, membranes, power supply, and control systems, can be substantial. These costs can serve as a barrier to widespread adoption, particularly in resource-limited settings [51].

Another limitation is the potential for electrode fouling and degradation. During electrochemical treatment, the accumulation of contaminants and the formation of precipitates on the electrode surfaces can reduce their effectiveness and lifespan. Fouling and degradation of electrodes necessitate regular maintenance, cleaning, or replacement, which can increase overall operational costs and reduce system efficiency. The development of electrode materials with improved resistance to fouling and degradation is an active area of research [52].

Moreover, the scalability and adaptability of electrochemical treatment processes to different wastewater compositions and treatment objectives require further attention. The performance of electrochemical treatment systems may vary depending on specific wastewater characteristics, such as pH, conductivity, and organic load. Optimization and customization of treatment parameters and system design for specific applications are necessary to ensure efficient and reliable operation [28].

To address these challenges and limitations, research efforts are directed towards improving the understanding of electrochemical treatment processes in field-scale applications. The development of advanced modeling and simulation tools can aid in predicting and optimizing system performance under various soil conditions and contaminant mixtures. The exploration of innovative electrode materials and designs can enhance electrode durability and reduce fouling. Additionally, advancements in sensor technologies and real-time monitoring can facilitate process control and ensure optimal performance [53].

6 Future Perspectives and Research Directions

Addressing the wastewater treatment challenge worldwide is imperative due to increasing population growth, urbanization, and industrialization. Traditional treatment methods often prove inadequate in removing emerging contaminants and achieving stringent effluent quality standards [54]. Electrochemical treatment has emerged as a promising alternative for wastewater treatment, offering several advantages such as high efficiency, versatility, and the potential for resource recovery. However, further research is necessary to optimize and advance this technology.

6.1 Advances in Electrode Materials and Reactor Design

The role of electrode materials in determining the efficiency and performance of electrochemical treatment systems is crucial. Recent research has focused on the development of novel electrode materials with enhanced catalytic activity, stability, and selectivity [55]. For instance, promising results in pollutant degradation and resource recovery have been demonstrated by graphene-based materials, metal-organic frameworks (MOFs), and nanostructured transition metal oxides. These advanced electrode materials offer larger surface areas, improved charge transfer kinetics, and better adsorption capacities, leading to enhanced treatment efficiency [56].

Moreover, reactor design is another area of research focus for electrochemical wastewater treatment. Novel reactor configurations, such as flow-through porous electrodes, three-dimensional electrodes, and packed-bed electrodes, have exhibited improved mass transfer, reduced energy consumption, and enhanced treatment performance. These advancements in reactor design aim to address the limitations of conventional systems, including electrode fouling, bubble generation, and inadequate mixing, thereby improving the overall efficiency of electrochemical treatment processes [57].

6.2 Integration with Renewable Energy Sources

To mitigate the environmental concerns associated with energy consumption in electrochemical treatment, the integration of renewable energy sources is being explored by researchers. The incorporation of solar, wind, and hydroelectric power can provide a sustainable and environmentally friendly energy supply for electrochemical processes. Photovoltaic panels, wind turbines, and hydropower systems can be directly connected to electrochemical reactors, supplying continuous and clean energy. This integration not only diminishes the reliance on fossil fuels but also enhances the overall sustainability and carbon footprint of the treatment process [58].

6.3 Optimization and Control Strategies for Improved Efficiency

Efficient operation and control of electrochemical treatment systems are essential to maximize pollutant removal and minimize energy consumption. Research is concentrating on the development of optimization and control strategies to achieve these objectives. Advanced process control techniques, such as model-based predictive control, artificial intelligence algorithms, and real-time monitoring systems, can be employed to optimize process parameters, electrode potentials, and flow rates. These strategies enable adaptive and autonomous control, ensuring optimal performance under varying operating conditions. Additionally, the integration of sensors and online analyzers facilitates real-time monitoring of key parameters, allowing for early detection of process deviations and prompt corrective actions [59].

6.4 Development of Cost-effective and Scalable Electrochemical Systems

To achieve widespread adoption of electrochemical treatment technologies, they must be cost-effective and scalable. Research efforts are directed towards developing economically viable systems by reducing the costs associated with electrode materials, catalysts, and energy consumption. The exploration of low-cost electrode materials, such as carbon-based materials and metal oxide composites, aims to minimize the overall system cost while maintaining high treatment efficiency. Additionally, the development of innovative electrode manufacturing techniques, such as electrodeposition and screen-printing, enables scalable and cost-effective production of electrodes [60].

7 Conclusions

Electrochemical treatment demonstrates significant potential for sustainable remediation and wastewater treatment. This review has examined various aspects of this technology, encompassing advances in electrode materials and reactor design, integration with renewable energy sources, optimization and control strategies, and the development of cost-effective and scalable systems. Despite the limitations and challenges associated with electrochemical techniques, such as heterogeneous soil conditions, the presence of complex contaminant mixtures, and the potential for electrode fouling and degradation, electrochemical treatment stands as a promising approach for sustainable remediation and wastewater treatment.

Harnessing the full potential of electrochemical treatment requires ongoing research and development in electrode materials, reactor design, renewable energy integration, optimization and control strategies, and cost-effective system development. This technology offers a viable solution to address the challenges of wastewater treatment, contributing to a more sustainable and environmentally conscious future. It is imperative for policymakers, industry stakeholders, and the broader scientific community to recognize the potentials and benefits of electrochemical treatments for sustainable remediation.

Future research should be directed towards overcoming the existing limitations and challenges by developing novel electrode materials, enhancing reactor designs, and implementing advanced control strategies. Furthermore, the integration of electrochemical treatment systems with renewable energy sources, as well as the development of cost-effective and scalable systems, should be prioritized. These efforts will not only improve the efficiency and applicability of electrochemical treatment technologies but also promote their widespread adoption in addressing the urgent need for sustainable wastewater management. By fostering collaboration and innovation, the scientific community can advance electrochemical treatment solutions, ultimately contributing to a cleaner and more sustainable future.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] R. Kumar, M. Qureshi, D. K. Vishwakarma, N. Al-Ansari, A. Kuriqi, A. Elbeltagi, and A. Saraswat, "A review on emerging water contaminants and the application of sustainable removal technologies," *Case Studies Chem. Environ. Eng.*, vol. 6, p. 100219, 2022. https://doi.org/10.1016/j.cscee.2022.100219

[2] O. D. Ogundele, A. J. Adewumi, and D. A. Oyegoke, "Phycoremediation: Algae as an effective agent for sustainable remediation and waste water treatment," *Environ. Earth Sci. Res. J.*, vol. 10, no. 1, pp. 7–17, 2023. https://doi.org/10.18280/eesrj.100102

[3] D. A. Wolfe, J. Michel, M. J. Hameedi, J. R. Payne, J. A. Galt, G. Watabayashi, J. Short, C. O'Claire, S. Rice, and J. Braddock, "The fate of the oil spilled from the exxon valdez," *Environ. Sci. Techno.*, vol. 28, no. 13, pp. 560A–568A, 2000.

[4] S. E. Hrudey and E. J. Hrudey, *Safe drinking water: lessons from recent outbreaks in affluent nations*. NRC Research Press, 2004.

[5] S. K. Sarkar, M. Saha, H. Takada, A. Bhattacharya, P. Mishra, and B. Bhattacharya, "Water quality management in the lower stretch of the river ganges, east coast of india: an approach through environmental education," *J. Clean. Prod.*, vol. 15, no. 16, pp. 1559–1567, 2007. https://doi.org/10.1016/j.jclepro.2006.07.030

[6] M. Hanna-Attisha, J. LaChance, R. C. Sadler, A. Champney Schnepp, and M. Hanna-Attisha, "Elevated blood lead levels in children associated with the flint drinking water crisis: a spatial analysis of risk and public health response," *Am. J. Public Health*, vol. 106, no. 2, pp. 283–290, 2016. https://doi.org/10.2105/ajph.2015.303003

[7] E. Rizzo, P. Bardos, L. Pizzol, A. Critto, E. Giubilato, A. Marcomini, C. Albano, D. Darmendrail, G. Döberl, M. Harclerode, N. Harries, P. Nathanail, C. Pachon, A. Rodriguez, H. Slenders, and G. Slenders, "Comparison of international approaches to sustainable remediation," *J. Environ. Manage*, vol. 184, pp. 4–17, 2016. https://doi.org/10.1016/j.jenvman.2016.07.062

[8] L. Wang, J. Rinklebe, F. M. Tack, and D. Hou, "A review of green remediation strategies for heavy metal contaminated soil," *Soil Use Manage*, vol. 37, no. 4, pp. 936–963, 2021. http://dx.doi.org/10.1111/sum.12717

[9] P. R. Rout, T. C. Zhang, P. Bhunia, and R. Y. Surampalli, "Treatment technologies for emerging contaminants in wastewater treatment plants: A review," *Sci. Total Environ.*, vol. 753, p. 141990, 2021. https://doi.org/10.1016/j.scitotenv.2020.141990

[10] O. O. Donde, "Wastewater management techniques: A review of advancement on the appropriate wastewater treatment principles for sustainability," *Environ. Manage. Sustain. Dev.*, vol. 6, no. 1, pp. 40–58, 2017. http://dx.doi.org/10.5296/emsd.v6i1.10137

[11] J. J. Trevino-Resendez, A. Medel, and Y. Meas, "Electrochemical technologies for treating petroleum industry wastewater," *Cur. Opin. Electroche.*, vol. 27, p. 100690, 2021. https://doi.org/10.1016/j.coelec.2021.100690

[12] J. Qiao and Y. Xiong, "Electrochemical oxidation technology: A review of its application in high-efficiency treatment of wastewater containing persistent organic pollutants," *J. Water Process Eng.*, vol. 44, p. 102308, 2021. https://doi.org/10.1016/j.jwpe.2021.102308

[13] S. O. Ganiyu, C. A. Martínez-Huitle, and M. A. Oturan, "Electrochemical advanced oxidation processes for wastewater treatment: Advances in formation and detection of reactive species and mechanisms," *Curr. Opin. Electroche.*, vol. 5, p. 100678, 2021. https://doi.org/10.1016/j.coelec.2020.100678

[14] I. Sires, E. Brillas, M. A. Oturan, M. A. Rodrigo, and M. Panizza, "Electrochemical advanced oxidation processes: today and tomorrow. a review," *Environ. Sci. Pollut. R.*, vol. 21, pp. 8336–8367, 2014.

[15] V. Devda, K. Chaudhary, S. Varjani, B. Pathak, A. K. Patel, R. R. Singhania, M. J. Taherzadeh, H. H. Ngo, J. W. C. Wong, W. Guo, and P. Chaturvedi, "Recovery of resources from industrial wastewater employing electrochemical technologies: Status, advancements and perspectives," *Bioengineered*, vol. 12, no. 1, pp. 4697–4718, 2021. https://doi.org/10.1080/21655979.2021.1946631

[16] A. K. Chopra, A. K. Sharma, and V. Kumar, "Overview of electrolytic treatment: An alternative technology for purification of wastewater," *Arch. Appl. Sci. R.*, vol. 3, no. 5, pp. 191–206, 2011.

[17] I. Sirés and E. Brillas, "Remediation of water pollution caused by pharmaceutical residues based on electrochemical separation and degradation technologies: A review," *Environ. Int.*, vol. 40, pp. 212–229, 2012. https://doi.org/10.1016/j.envint.2011.07.012

[18] M. Panizza and G. Cerisola, "Direct and mediated anodic oxidation of organic pollutants," *Chem. Rev.*, vol. 109, no. 12, pp. 6541–6569, 2009. https://doi.org/10.1021/cr9001319

[19] O. Scialdone, "Electrochemical oxidation of organic pollutants in water at metal oxide electrodes: A simple theoretical model including direct and indirect oxidation processes at the anodic surface," *Electrochim. Acta.*, vol. 54, no. 26, pp. 6140–6147, 2009. https://doi.org/10.1016/j.electacta.2009.05.066

[20] S. W. da Silva, J. B. Welter, L. L. Albornoz, A. N. A. Heberle, J. Z. Ferreira, and A. M. Bernardes, "Advanced electrochemical oxidation processes in the treatment of pharmaceutical containing water and wastewater: A

review," *Curr. Pollut. Rep.*, vol. 7, pp. 146–159, 2021.

[21] F. C. Moreira, R. A. Boaventura, E. Brillas, and V. J. Vilar, "Electrochemical advanced oxidation processes: A review on their application to synthetic and real wastewaters," *Appl. Catal. B: Environ.*, vol. 202, pp. 217–261, 2017. http://dx.doi.org/10.1016/j.apcatb.2016.08.037

[22] Y. Feng, L. Yang, J. Liu, and B. E. Logan, "Electrochemical technologies for wastewater treatment and resource reclamation," *Environ. Sci.: Water. Res. Technol.*, vol. 2, no. 5, pp. 800–831, 2016.

[23] G. Zhang, J. Ruan, and T. Du, "Recent advances on photocatalytic and electrochemical oxidation for ammonia treatment from water/wastewater," *ACS EST Eng.*, vol. 1, no. 3, pp. 310–325, 2020. http://dx.doi.org/10.1021/acsestengg.0c00186

[24] T. Muddemann, D. Haupt, M. Sievers, and U. Kunz, "Electrochemical reactors for wastewater treatment," *ChemBioEng Rev.*, vol. 6, no. 5, pp. 142–156, 2019.

[25] E. Brillas and C. A. Martinez-Huitle, "Decontamination of wastewaters containing synthetic organic dyes by electrochemical methods. an updated review," *Appl. Catal. B: Environ.*, vol. 166, pp. 603–643, 2015. https://doi.org/10.1016/j.apcatb.2014.11.016

[26] P. V. Nidheesh, M. Zhou, and M. A. Oturan, "An overview on the removal of synthetic dyes from water by electrochemical advanced oxidation processes," *Chemosphere*, vol. 197, pp. 210–227, 2018. https://doi.org/10.1016/j.chemosphere.2017.12.195

[27] C. A. Martinez-Huitle, M. A. Rodrigo, I. Sires, and O. Scialdone, "Single and coupled electrochemical processes and reactors for the abatement of organic water pollutants: A critical review," *Chem. Rev.*, vol. 115, no. 24, pp. 13 362–13 407, 2015. https://doi.org/10.1021/acs.chemrev.5b00361

[28] M. A. Oturan and J. J. Aaron, "Advanced oxidation processes in water/wastewater treatment: Principles and applications. A review," *Crit. Rev. Env. Sci. Tec.*, vol. 159, pp. 2577–2641, 2014.

[29] S. Vasudevan and M. A. Oturan, "Electrochemistry: As cause and cure in water pollution—an overview," *Environ. Chem. Lett.*, vol. 12, pp. 97–108, 2014. http://dx.doi.org/10.1007/s10311-013-0434-2

[30] T. Zheng, J. Wang, Q. Wang, H. Meng, and L. Wang, "Research trends in electrochemical technology for water and wastewater treatment," *Appl. Water. Sci.*, vol. 7, pp. 13–30, 2017.

[31] W. Ren, C. Cheng, P. Shao, X. Luo, H. Zhang, S. Wang, and X. Duan, "Origins of electron-transfer regime in persulfate-based nonradical oxidation processes," *Environ. Sci. Technol.*, vol. 56, no. 1, pp. 78–97, 2021. https://doi.org/10.1021/acs.est.1c05374

[32] S. Samsami, M. Mohamadizaniani, M. H. Sarrafzadeh, E. R. Rene, and M. Firoozbahr, "Recent advances in the treatment of dye-containing wastewater from textile industries: Overview and perspectives," *Process Saf. Environ.*, vol. 143, pp. 138–163, 2020. https://doi.org/10.1016/j.psep.2020.05.034

[33] E. Fekete, B. Lengyel, and T. Cserfalvi, "Electrocoagulation: An electrochemical process for water clarification," *J. Electrochem. Sci. Eng.*, vol. 6, no. 1, pp. 57–65, 2016. https://doi.org/10.5599/jese.218

[34] M. Ben-Sasson, Y. M. Lin, and A. Adin, "Electrocoagulation-membrane filtration hybrid system for colloidal fouling mitigation of secondary-effluent," *Sep. Purif. Technol.*, vol. 82, pp. 63–70, 2011. https://doi.org/10.1016/j.seppur.2011.08.020

[35] M. Solak, M. Kılıc, H. Yuksel, and A. Sencan, "Removal of suspended solids and turbidity from marble processing wastewaters by electrocoagulation: Comparison of electrode materials and electrode connection systems," *J. Hazard. Mater.*, vol. 72, no. 1, pp. 345–352, 2009.

[36] J. N. Hakizimana, N. Najid, B. Gourich, C. Vial, Y. Stiriba, and J. Naja, "Hybrid electrocoagulation/electroflotation/electrodisinfection process as a pretreatment for seawater desalination," *Chem. Eng. Sci.*, vol. 170, pp. 530–541, 2017. https://doi.org/10.1016/j.ces.2017.04.029

[37] T. C. Timmes, H. C. Kim, and B. A. Dempsey, "Electrocoagulation pretreatment of seawater prior to ultrafiltration: Pilot-scale applications for military water purification systems," *Desalination*, vol. 250, pp. 6–13, 2010. https://doi.org/10.1016/j.desal.2009.03.021

[38] F. E. Titchou, H. Zazou, H. Afanga, J. El Gaayda, R. A. Akbour, P. V. Nidheesh, and M. Hamdani, "An overview on the elimination of organic contaminants from aqueous systems using electrochemical advanced oxidation processes," *J. Water Process Eng.*, vol. 41, p. 102040, 2021. https://doi.org/10.1016/j.jwpe.2021.102040

[39] O. Ganzenko, D. Huguenot, E. D. Van Hullebusch, G. Esposito, and M. A. Oturan, "Electrochemical advanced oxidation and biological processes for wastewater treatment: A review of the combined approaches," *Environ. Sci. Pollut. Res.*, vol. 21, pp. 8493–8524, 2014. https://doi.org/10.1007/s11356-014-2770-6

[40] L. Gurreri, A. Cipollina, A. Tamburini, and G. Micale, *Electrodialysis for wastewater treatment—Part I: Fundamentals and municipal effluents*. Elsevier, 2020, pp. 141–192. https://doi.org/10.1016/b978-0-12-816823-3.00007-1

[41] B. Van der Bruggen, *Advances in electrodialysis for water treatment*. Elsevier, 2015, pp. 185–203. https:

//doi.org/10.1016/b978-1-78242-121-4.00006-x

[42] J. Juve, F. Christensen, Y. Wang, and Z. Wei, "Electrodialysis for metal removal and recovery: A review," *Chem. Eng. J.*, vol. 435, p. 134857, 2022. https://doi.org/10.1016/j.cej.2022.134857

[43] R. L. Zornitta and L. A. Ruotolo, "Simultaneous analysis of electrosorption capacity and kinetics for cdi desalination using different electrode configurations," *Chem. Eng. J.*, vol. 332, pp. 33–41, 2018.

[44] R. Chen, T. Sheehan, J. L. Ng, M. Brucks, and X. Su, "Capacitive deionization and electrosorption for heavy metal removal," *Environ. Sci: Water Res. Technol.*, vol. 6, no. 2, pp. 258–282, 2020.

[45] Y. Mei and C. Y. Tang, "Recent developments and future perspectives of reverse electrodialysis technology: A review," *Desalination*, vol. 425, pp. 156–174, 2018. https://doi.org/10.1016/j.desal.2017.10.021

[46] L. Gurreri, A. Tamburini, and G. Cipollina, A. andMicale, "Electrodialysis applications in wastewater treatment for environmental protection and resources recovery: A systematic review on progress and perspectives," *Membranes*, vol. 10, no. 7, p. 146, 2020. https://doi.org/10.3390/membranes10070146

[47] S. Al-Amshawee, M. Y. B. M. Yunus, A. A. M. Azoddein, D. G. Hassell, I. H. Dakhil, and H. A. Hasan, "Electrodialysis desalination for water and wastewater: A review," *Chem. Eng. J.*, vol. 380, p. 122231, 2020. https://doi.org/10.1016/j.cej.2019.122231

[48] S. S. Kim, S. J. Han, and Y. S. Cho, "Electrokinetic remediation strategy considering ground strate: A review," *Geosci. J.*, vol. 6, pp. 57–75, 2002.

[49] K. Reddy, *Electrokinetic remediation of soils at complex contaminated sites*. CRC Press, 2013, pp. 131–147. https://doi.org/10.1201/b15004-14

[50] S. Garcia-Segura, J. D. Ocon, and M. N. Chong, "Electrochemical oxidation remediation of real wastewater effluents—a review," *Process Saf. Environ.*, vol. 113, pp. 48–67, 2018.

[51] R. Dewil, D. Mantzavinos, I. Poulios, and M. A. Rodrigo, "New perspectives for advanced oxidation processes," *J. Environ. Manage.*, vol. 195, pp. 93–99, 2017. https://doi.org/10.1016/j.envpol.2020.114634

[52] S. Feijoo, S. Estévez, M. Kamali, R. Dewil, and M. T. Moreira, "Scale-up modelling and life cycle assessment of electrochemical oxidation in wastewater treatment," *Chem. Eng. J.*, vol. 455, p. 140627, 2023. https://doi.org/10.1016/j.cej.2022.140627

[53] S. Chae, H. Kim, J. G. Hong, J. Jang, M. Higa, M. Pishnamazi, J. Y. Choi, R. C. Walgama, C. Bae, I. S. Kim, and J. S. Park, "Clean power generation from salinity gradient using reverse electrodialysis technologies: Recent advances, bottlenecks, and future direction," *Chem. Eng. J.*, vol. 452, p. 139482, 2023.

[54] M. K. Shahid, A. Kashif, A. Fuwad, and Y. Choi, "Current advances in treatment technologies for removal of emerging contaminants from water–a critical review," *Coordin. Chem. Rev.*, vol. 442, p. 213993, 2021. https://doi.org/10.1016/j.ccr.2021.213993

[55] M. Priyadarshini, A. Ahmad, S. Das, and M. M. Ghangrekar, "Application of innovative electrochemical and microbial electrochemical technologies for the efficacious removal of emerging contaminants from wastewater: A review," *J. Environ. Chem. Eng.*, vol. 10, no. 5, p. 108230, 2022. https://doi.org/10.1016/j.jece.2022.108230

[56] D. Clematis, M. Delucchi, and M. Panizza, "Electrochemical technologies for wastewater treatment at pilot plant scale," *Curr. Opin. Electroche.*, vol. 37, p. 101172, 2022. https://doi.org/10.1016/j.coelec.2022.101172

[57] H. Hou, K. M. Zeinu, S. Gao, B. Liu, J. Yang, and J. Hu, "Recent advances and perspective on design and synthesis of electrode materials for electrochemical sensing of heavy metals," *Energy Environ. Mater.*, vol. 1, no. 3, pp. 113–131, 2018. http://dx.doi.org/10.1002/eem2.12011

[58] P. Srimuk, X. Su, J. Yoon, D. Aurbach, and V. Presser, "Charge-transfer materials for electrochemical water desalination, ion separation and the recovery of elements," *Nat. Rev. Mater.*, vol. 5, no. 7, pp. 517–538, 2020. http://dx.doi.org/10.1038/s41578-020-0193-1

[59] V. H. Cong, Y. Sakakibara, M. Komori, N. Kishimoto, T. Watanabe, I. Mishima, I. Ihara, T. Tanaka, Y. Yoshida, and H. Ozaki, "Recent developments in electrochemical technology for water and wastewater treatments," *J. Water Environ. Technol.*, vol. 14, no. 2, pp. 25–36, 2016. http://dx.doi.org/10.2965/jwet.15-029

[60] S. Garcia-Segura, X. Qu, P. J. Alvarez, B. P. Chaplin, W. Chen, and e. a. Crittenden, J. C., "Opportunities for nanotechnology to enhance electrochemical treatment of pollutants in potable water and industrial wastewater–a perspective," *Environ. Sci: Nano*, vol. 7, no. 8, pp. 2178–2194, 2020. https://www.x-mol.com/paperRedirect/1274089835229376512