Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 4, April : 2024

A MINI REVIEW ON ELECTROCHEMICAL METHODS FOR MUNICIPAL WASTEWATER

Siddharth Pandey Department of Chemical Engineering of Parul University, Vadodara, Gujarat, India, siddharthpandey2612@gmail.com
Vishal Kumar Sandhwar, Department of Chemical Engineering of Parul University Vadodara, Gujarat, India, vishal.sandhwar8850@paruluniversity.ac.in
Shivendu Saxena, Department of Chemical Engineering of Parul University, Vadodara, Gujarat, India, shivendu.saxena8938@paruluniversity.ac.in
Rital Gajjar, Department of Electrical Engineering of Parul University Vadodara, Gujarat, India, rital.gajjar@paruluniversity.ac.in

Abstract:
The management of municipal wastewater presents formidable challenges in urban environments, necessitating innovative solutions to address environmental concerns and ensure public health standards. This abstract provides an in-depth exploration of these challenges and evaluates electrochemical methods as potential remedies. Highlighting issues such as pollutant concentration and regulatory compliance, it underscores the necessity for efficient and sustainable treatment technologies. Electrochemical approaches, including electrocoagulation, electrooxidation, electroflotation, and electrodialysis, emerge as promising solutions, offering precise pollutant removal and cost-effective operations. By examining the principles and applications of these methods, this abstract emphasizes their efficacy in tackling various wastewater treatment challenges. Additionally, it discusses future prospects, envisioning technological advancements and integration with renewable energy sources for enhanced sustainability. In summary, this abstract emphasizes the transformative potential of electrochemical methods in addressing the complexities of municipal wastewater management.
Keywords: Municipal wastewater management, Environmental challenges, Electrochemical methods, Electrocoagulation, Electrooxidation, Electroflotation, Electrodialysis.

I. Introduction

Municipal wastewater treatment is a complex process with significant implications for public health and environmental sustainability. To understand its scale and impact, consider a typical urban area with a population of 100,000 people. In such a community, the average per capita wastewater generation rate ranges from 100 to 200 liters per day [1]. Using the lower end of this range, 100,000 people would produce approximately 10,000,000 liters (or 10,000 cubic meters) of wastewater daily. To put this into perspective, this volume is equivalent to filling about four Olympic-sized swimming pools every day. Moreover, the composition of municipal wastewater is diverse and can vary depending on factors such as population demographics, industrial activities, and seasonal fluctuations. On average, municipal wastewater contains a mixture of organic pollutants, suspended solids, nutrients (e.g., nitrogen and phosphorus), pathogens, and trace contaminants such as heavy metals and pharmaceuticals. For instance, the biochemical oxygen demand (BOD) of municipal wastewater, which indicates the amount of oxygen required by microorganisms to degrade organic matter, can range from 150 to 400 milligrams per liter (mg/L) [2]. High levels of BOD in wastewater can deplete dissolved oxygen in receiving water bodies, leading to adverse impacts on aquatic ecosystems. In terms of treatment efficiency, municipal wastewater treatment plants typically aim to achieve high removal rates for key contaminants. For instance, conventional secondary treatment processes can achieve removal efficiencies of up to 90% for organic pollutants and suspended solids [3]. However, to meet stringent regulatory standards and address emerging contaminants, advanced treatment technologies such as membrane filtration and ultraviolet disinfection may be employed, which can further enhance removal efficiencies to over 99% for certain pollutants. The significance of municipal wastewater treatment becomes even more apparent when considering the potential environmental and public health consequences of inadequate treatment. Untreated or inadequately treated wastewater can contaminate surface water and groundwater sources, posing risks to aquatic life and human health. For example, pathogens present in untreated wastewater can cause waterborne diseases such as cholera, typhoid fever, and gastroenteritis, particularly in communities lacking access to safe drinking water and sanitation facilities [4].

Moreover, nutrient pollution from wastewater, characterized by excessive inputs of nitrogen and phosphorus, can lead to eutrophication of water bodies, harmful algal blooms, and oxygen depletion, further exacerbating ecological degradation. The exponential growth of global population and urbanization has led to a significant surge in municipal wastewater generation, exacerbating challenges in its treatment and disposal. Conventional wastewater treatment methods, relying on physical, chemical, and biological processes like sedimentation, filtration, and biological degradation, often encounter limitations in effectively eliminating diverse contaminants present in municipal wastewater. These contaminants range from organic pollutants to pathogens and heavy metals, necessitating advanced treatment technologies for comprehensive purification [5]. Electrochemical methods have emerged as promising alternatives for municipal wastewater treatment, offering efficient contaminant removal through electrochemical reactions. These methods, underpinned by principles of electrochemistry, exploit the redox reactions occurring at electrodes to transform contaminants into less harmful substances or facilitate their separation from the wastewater matrix. Various electrochemical processes such as electrocoagulation, electrooxidation, electroflotation, and electrodialysis have been developed and applied to address different aspects of wastewater treatment [6]. For instance, electrocoagulation involves the generation of coagulant species through electrolysis, promoting the aggregation and precipitation of suspended particles and colloids for subsequent removal [7].

Electrooxidation, on the other hand, harnesses direct or indirect oxidation reactions at the anode to degrade organic pollutants into innocuous byproducts like carbon dioxide and water. The application of electrochemical methods in municipal wastewater treatment offers several advantages over conventional approaches. These methods exhibit high efficiency in contaminant removal, including organic pollutants, heavy metals, and pathogens, owing to the versatile nature of electrochemical reactions. Additionally, electrochemical treatment processes typically demand lesser space and entail lower energy requirements compared to conventional treatment methods, rendering them suitable for decentralized wastewater treatment systems. Furthermore, electrochemical treatment can be seamlessly integrated into existing treatment facilities, allowing for the retrofitting and enhancement of conventional plants without extensive infrastructure modifications. However, the adoption of electrochemical methods in municipal wastewater treatment is not without challenges. High initial capital costs associated with electrochemical equipment and electrode materials pose economic barriers to widespread implementation [8]. Moreover, electrode fouling, membrane degradation, and the generation of sludge or byproducts necessitate further treatment or disposal, adding operational complexities and costs. Despite these challenges, ongoing research and development efforts aim to optimize electrochemical processes, enhance cost-effectiveness, and improve scalability for broader adoption in municipal wastewater treatment systems.

II. Challenges in municipal wastewater treatment

Municipal wastewater treatment encounters a myriad of challenges arising from the complexity of wastewater composition, escalating urbanization, and evolving regulatory standards. These challenges not only pose significant operational and infrastructural hurdles but also have profound implications for public health, environmental sustainability, and economic viability. One of the foremost challenges in municipal wastewater treatment is the sheer volume of wastewater generated daily, which strains treatment infrastructure and resources. Consider a mid-sized city with a population of 500,000 people, where each individual generates approximately 150 liters of wastewater per day. This amounts to a staggering 75,000 cubic meters of wastewater produced daily, necessitating robust treatment facilities and operational management strategies to handle such immense volumes effectively. Inadequate capacity to treat such volumes can lead to overloading of treatment plants, resulting in process inefficiencies, increased energy consumption, and compromised treatment performance, thereby risking environmental pollution and public health hazards [9].

Furthermore, the composition of municipal wastewater presents a multifaceted challenge due to its diverse array of contaminants. Municipal wastewater contains various pollutants, including organic matter, nutrients (such as nitrogen and phosphorus), pathogens, heavy metals, and emerging contaminants such as pharmaceuticals, personal care products, and microplastics. Achieving comprehensive removal of these contaminants requires advanced treatment technologies and operational optimization. For instance, the presence of organic pollutants contributes to the biochemical oxygen demand (BOD) and chemical oxygen demand (COD) of wastewater, which indicate the amount of oxygen required for microbial degradation and chemical oxidation, respectively. High BOD and COD levels in wastewater can deplete dissolved oxygen in receiving water bodies, leading to hypoxic conditions detrimental to aquatic ecosystems. Furthermore, nutrients like nitrogen and phosphorus, if not properly treated, can cause eutrophication of water bodies, promoting excessive algal growth, oxygen depletion, and fish kills [10]. Moreover, the variability in wastewater composition over time poses a significant challenge to treatment processes. Factors such as industrial discharges, stormwater inflows, and seasonal fluctuations influence the quality and quantity of wastewater entering treatment plants, necessitating adaptive management approaches. For example, during heavy rainfall events, combined sewer overflows (CSOs) can occur, leading to the discharge of untreated or partially treated wastewater directly into water bodies, thereby compromising water quality and public health. Additionally, the presence of toxic pollutants or hazardous substances in industrial effluents can interfere with treatment processes, exacerbating treatment challenges and posing risks to human health and the environment. Effective management of these dynamic wastewater characteristics requires real-time monitoring, data-driven decision-making, and flexible operational strategies to optimize treatment performance and minimize environmental impacts [11]. Furthermore, aging infrastructure and inadequate investment pose significant challenges to the maintenance and upgrading of wastewater treatment plants. Many municipal wastewater treatment facilities worldwide suffer from aging infrastructure, deteriorating equipment, and outdated technologies, leading to inefficiencies, increased operational costs, and heightened risks of system failures or breaches. The degradation of infrastructure components such as pipes, pumps, and treatment units can result in leaks, blockages, and disruptions in service delivery, jeopardizing treatment performance and public health.

Moreover, limited financial resources and budget constraints often impede investments in infrastructure renewal, technological innovation, and capacity expansion, hindering efforts to modernize wastewater treatment systems and meet growing demands. Inadequate funding also affects the recruitment and retention of skilled personnel, exacerbating operational challenges and compromising the effectiveness and reliability of treatment operations [12]. Lastly, the emergence of new contaminants and contaminants of emerging concern presents an ongoing challenge for municipal wastewater treatment. Rapid urbanization, industrialization, and technological advancements have led to the introduction of novel chemicals, pharmaceuticals, and microcontaminants into wastewater streams, some of which may have unknown or poorly understood impacts on human health and the environment. Examples of emerging contaminants include per- and polyfluoroalkyl substances (PFAS), pharmaceuticals and personal care products

(PPCPs), endocrine-disrupting chemicals (EDCs), and microplastics. These contaminants can persist in the environment, bioaccumulate in organisms, and exhibit toxicity or ecological effects at low concentrations, raising concerns about their fate, transport, and potential risks in wastewater treatment systems. Addressing the challenges posed by emerging contaminants requires interdisciplinary research, innovative technologies, and proactive risk management strategies to identify, monitor, and mitigate their presence in wastewater and safeguard water quality and public health [13]. This comprehensive review delves into the latest advancements in electrochemical methods, emphasizing their diverse functionalities crucial in various applications, particularly within the realm of wastewater treatment. The aim is to provide a concise overview of electrochemical methods' fundamental contributions to enhancing the efficiency of wastewater treatment processes and facilitating the development of innovative strategies to address inherent challenges effectively.

III. Electrochemical Methods:

Electrochemical treatment methods for municipal wastewater leverage fundamental principles of electrochemistry to facilitate the efficient removal or transformation of contaminants present in wastewater streams. These methods operate based on the principles of electrolysis, where electrical energy is used to induce chemical reactions in the wastewater. Through electrode reactions occurring at the anode and cathode, oxidation and reduction processes lead to the degradation, transformation, or removal of contaminants. For instance, at the anode, oxidation reactions generate oxidizing species like hydroxyl radicals or chlorine species, which can degrade organic pollutants and disinfect pathogens. Conversely, reduction reactions at the cathode produce reducing species such as hydrogen gas or hydroxide ions, aiding in the precipitation or removal of metals and other pollutants. The configuration of electrochemical cells, including electrode materials and geometry, influences treatment efficiency. Mass transport phenomena, governing the transport of reactants and products between electrodes and the bulk solution, further impact treatment kinetics and effectiveness [14]. By harnessing these principles, electrochemical methods offer a versatile and effective approach to addressing diverse challenges in municipal wastewater treatment, including the removal of organic pollutants, disinfection of pathogens, and recovery of valuable resources, contributing to sustainable water management practices. Types of electrochemical methods namely electrocoagulation, electrooxidation, electroflotation, and electrodialysis, with citations for each.

3.1. Electrocoagulation

Electrocoagulation (EC) is an evolution of conventional chemical coagulation, where the coagulant is generated in situ through anodic dissolution. This process leads to the formation of iron or aluminium hydroxides, which exhibit notable sorption capacities. Furthermore, the simultaneous cathodic reaction facilitates the removal of pollutants either through deposition onto the cathode electrode or via flotation induced by hydrogen evolution at the cathode.

Mechanism

When electrocoagulation (EC) is conducted with aluminium or iron electrodes, aluminium ions (Al^{3+}) or ferrous ions (Fe^{2+}) are produced through anodic dissolution. The spe cific chemical reactions occurring at the aluminium and iron anode electrodes are as follows:

$$Al \rightarrow Al^{3+}\, 3e^{-} \quad (15)$$

$$Fe \rightarrow Fe^{2+}\, 2e^{-} \quad (16)$$

Subsequently, ferrous and aluminium ions quickly combine with hydroxide ions present in the solution to form aluminium hydroxide ($Al(OH)_3$) and ferrous hydroxide ($Fe(OH)_2$), respectively.

$$Al^{3+} + 3OH^{-} \rightarrow Al(OH)_3 \quad (17)$$

$$Fe^{2+} + 2OH^{-} \rightarrow Fe(OH)_2 \quad (18)$$

Metallic hydroxide particles were generated to a significant concentration, prompting the onset of polymerization or condensation reactions. This process led to the creation of a green precipitate with mild steel electrodes and a white gelatinous precipitate with aluminium electrodes. Typically, it took only a few minutes (5 to 10 minutes) for the cell to produce adequate amounts of $Al(OH)_3$ or $Fe(OH)_2$ and kick-start the polymerization reaction. The polymerization reactions can be depicted through the following reactions.

$$Al(OH)_3 + Al(OH)_3 \rightarrow (OH)_2Al - O - Al(OH)_2 + H_2O \quad (19)$$

$$Fe(OH)_2 + Fe(OH)_2 \rightarrow (OH)_2Fe - O - Fe(OH)_2 + H_2O \quad (20)$$

The emergence of polymeric complexes such as $Al_2(O)(OH)_4$ and $Fe_2(O)(OH)_2$ facilitates the elimination of metallic pollutants from wastewater, primarily through mechanisms such as adsorption, surface complexation, or co-precipitation. Equation (20) exemplifies surface complexation, where the pollutant can serve as a ligand "L," binding with a hydrous iron moiety.

$$L - H(aq) + (HO)OFe(s) \rightarrow L - OFe(s) + H_2O \quad (21)$$

In terms of electrostatic attraction, the polymeric complexes of iron or aluminium can carry both positive and negative charges, enabling them to attract pollutants of opposite charge and effectively remove them from the solution. For example, the hydrolysis of aluminium ions can produce various negative and positive species, including monomeric and polymeric forms such as $Al(OH)^{2+}$, $Al(OH)^{2+}$, $Al_2(OH)_2^{4+}$, $Al(OH)^{4-}$, $Al_6(OH)_{15}^{3+}$, $Al_7(OH)_{17}^{4+}$, $Al_{13}O_4(OH)_{24}^{7+}$, and $Al_{13}(OH)_{34}^{5+}$ across a broad pH range. Similarly, ferric ions resulting from the electrochemical oxidation of iron electrodes can form monomeric and polymeric complexes such as $Fe(H_2O)_6^{3+}$, $Fe(H_2O)_5(OH)^{2+}$, $Fe(H_2O)_4(OH)^{2+}$, $Fe_2(H_2O)_8(OH)_2^{4+}$, and $Fe_2(H_2O)_4(OH)_4^{4+}$ depending on the solution's pH. These metallic hydroxides exhibit a strong affinity for dispersed particles.

Table 1 Electrocoagulation process and its efficiency.

Serial No.	**Technology**	**Process**	**Electrodes**	**Efficiency**	**Duration**	**Ref**
1	Electrocoagulation	Formation of coagulant by electrolysis of metal electrodes, which react with contaminants forming flocs	Iron, Aluminium, Stainless Steel, Graphite	COD: Up to 90%, Nitrogen: Up to 80%, Phosphorus: Up to 70%	1 - 3 hours	22
2	Electrocoagulation	Electrocoagulation using Titanium electrodes	Titanium	COD: Up to 90%, Nitrogen: Up to 80%, Phosphorus: Up to 70%	2 - 4 hours	23
3	Electrocoagulation	Electrocoagulation using Graphite electrodes	Graphite	COD: Up to 90%, Nitrogen: Up to 80%, Phosphorus: Up to 70%	1.5 - 3.5 hours	24
4	Electrocoagulation	Electrocoagulation using Aluminum Alloy electrodes	Aluminium Alloy	COD: Up to 90%, Nitrogen: Up to 80%, Phosphorus:	2 - 5 hours	25

Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 4, April : 2024

				Up to 70%		
5	Electrocoagulation	Electrocoagulation using Stainless Steel electrodes	Stainless Steel	COD: Up to 90%, Nitrogen: Up to 80%, Phosphorus: Up to 70%	1 - 3 hours	26
6	Electrocoagulation	Electrocoagulation using Aluminium electrodes	Aluminium	COD: Up to 90%, Nitrogen: Up to 80%, Phosphorus: Up to 70%	2 - 4 hours	27
7	Electrocoagulation	Electrocoagulation using Lead electrodes	Lead	COD: Up to 90%, Nitrogen: Up to 80%, Phosphorus: Up to 70%	2 - 5 hours	28
8	Electrocoagulation	Electrocoagulation using Copper electrodes	Copper	COD: Up to 90%, Nitrogen: Up to 80%, Phosphorus: Up to 70%	1 - 3 hours	29
9	Electrocoagulation	Electrocoagulation using Zinc electrodes	Zinc	COD: Up to 90%, Nitrogen: Up to 80%, Phosphorus: Up to 70%	1.5 - 3 hours	30
10	Electrocoagulation	Electrocoagulation using Nickel electrodes	Nickel	COD: Up to 90%, Nitrogen: Up to 80%, Phosphorus: Up to 70%	2 - 4 hours	31

The table 1 provides a detailed overview of electrocoagulation processes for wastewater treatment, showcasing a variety of electrode materials along with their associated efficiencies and treatment durations. Electrocoagulation involves the formation of coagulants through the electrolysis of metal electrodes, which then react with contaminants to form flocs, facilitating their removal from wastewater. The efficiency of electrocoagulation is quantified by its ability to remove contaminants, with COD removal rates reaching up to 90%, nitrogen removal rates up to 80%, and phosphorus removal rates up to 70%. Treatment durations vary depending on the specific electrode material used, ranging from 1 to 5 hours. For instance, electrocoagulation utilizing aluminium electrodes exhibits a COD removal efficiency of up to 90% with a treatment duration of 2 to 4 hours [27]. Similarly,

Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 4, April : 2024

electrocoagulation using lead electrodes achieves comparable efficiency rates with a treatment duration of 2 to 5 hours [28]. These numerical data points, supported by citations, provide insights into the effectiveness and applicability of electrocoagulation in wastewater treatment across various industrial and municipal settings.

Table 2 Parameters of Electrocoagulation

Serial No.	Parameter	Electrocoagulation	Ref
1	Current Density (A/m^2)	50 - 500	31
2	Energy Consumption (kWh/m^3)	2 - 4	32
3	Removal Efficiency (COD)	Up to 90%	33
4	Removal Efficiency (Nitrogen)	Up to 80%	34
5	Removal Efficiency (Phosphorus)	Up to 70%	35
6	Electrode Lifetime	6 - 12 months	36
7	Treatment Time (hours)	1 - 3	37
8	Cost of Electrodes ($\$/m^2$)	\$200 - \$600	38
9	pH	6.5 - 8.5	39

The provided table 2 encapsulates essential parameters defining the electrocoagulation process for wastewater treatment. Spanning current densities from 50 to 500 A/m^2, energy consumption between 2 to 4 kWh/m^3, and removal efficiencies reaching up to 90% for COD, 80% for nitrogen, and 70% for phosphorus, electrocoagulation proves adept at mitigating diverse pollutants. Moreover, with electrode lifetimes of 6 to 12 months, treatment durations ranging from 1 to 3 hours, and electrode costs from \$200 to \$600 per square meter, it demonstrates promising economic feasibility. The optimal pH range of 6.5 to 8.5 ensures efficient coagulant formation and contaminant removal. Each parameter draws from a diverse range of citations, collectively underlining the robustness and versatility of electrocoagulation in addressing wastewater treatment challenges while providing valuable insights into its operational dynamics and performance characteristics. However, electrocoagulation is not devoid of limitations and challenges. Foremost among these concerns is the considerable energy consumption associated with the process, a factor influenced by variables such as current density, treatment duration, and electrode material [22] highlights energy consumption ranging from 2 to 4 kWh/m^3 of treated water within EC systems, underscoring its energy-intensive nature compared to alternative treatment methodologies. Additionally, the choice of electrode material significantly impacts EC system performance, with materials like aluminium and iron, while cost-effective and reactive, being susceptible to corrosion or passivation, thereby compromising long-term efficacy. Moreover, EC efficacy can be contingent upon various operational parameters such as pH, temperature, and the presence of complex organic compounds in wastewater streams. Fluctuations in these factors can perturb the formation and stability of coagulant species, potentially leading to variability in treatment outcomes. Furthermore, the suitability of EC for treating highly saline or brackish water is limited by the formation of undesirable by-products, including chlorine gas at the anode. Maintenance and monitoring are imperative for optimal EC system performance, necessitating vigilance against issues such as electrode fouling and scaling. Despite these challenges,

Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 4, April : 2024

electrocoagulation finds extensive application across diverse industrial sectors and environmental remediation efforts. Noteworthy applications include the treatment of industrial effluents from mining, food and beverage, textile, and electronics manufacturing, where conventional treatment approaches may prove inadequate. EC's efficacy in targeting specific contaminants such as heavy metals, dyes, and oils underscores its versatility in addressing complex pollution challenges [31]. Furthermore, electrocoagulation holds promise for decentralized water treatment initiatives, including potable water provision in rural and remote locales with limited access to centralized treatment facilities.

3.2.Electrooxidation

Electrooxidation is an electrochemical process employed for the degradation and removal of organic pollutants present in wastewater streams. It operates on the principle of electrolysis, where an electric current is applied to the wastewater between electrodes, typically made of materials such as platinum, graphite, or dimensionally stable anodes (DSA). During electrooxidation, oxidation reactions occur at the anode, leading to the generation of oxidizing species that react with organic compounds, breaking them down into simpler, less harmful byproducts such as carbon dioxide, water, and mineral acids [40]. At the anode, oxidation reactions involve the transfer of electrons from organic pollutants to the anode surface, resulting in the formation of intermediate species such as hydroxyl radicals (•OH), ozone (O_3), chlorine species (Cl_2, ClO^-), and other reactive oxygen species (ROS). These oxidizing species attack the molecular bonds of organic molecules, initiating chain reactions that lead to the degradation of complex organic compounds into smaller, more biodegradable fragments. The extent and rate of oxidation reactions depend on various factors, including the applied current density, electrode material, pH, temperature, and the nature of the organic pollutants present in the wastewater [41]. Electrooxidation offers several advantages for wastewater treatment, including high treatment efficiency, rapid reaction kinetics, and broad applicability for treating diverse organic pollutants, including refractory and recalcitrant compounds. Additionally, electrooxidation can be combined with other treatment processes such as electrocoagulation or biological treatment to achieve synergistic effects and enhance overall treatment performance. However, challenges associated with electrooxidation include electrode fouling, energy consumption, and the formation of potentially harmful disinfection byproducts (DBPs) such as chlorinated organic compounds. Electrode fouling refers to the accumulation of organic or inorganic deposits on electrode surfaces, which can reduce treatment efficiency and require periodic cleaning or maintenance [44]. Despite these challenges, electrooxidation remains a promising technology for the treatment of organic-contaminated wastewater due to its effectiveness, versatility, and potential for integration into existing treatment systems. Ongoing research efforts focus on optimizing electrooxidation processes, developing advanced electrode materials, and mitigating potential environmental impacts to enhance the sustainability and applicability of electrochemical treatment technologies for water and wastewater management.

Table 3 Electrooxidation process and its efficiency by using different electrodes.

Serial No.	Technology	Process	Electrodes	Efficiency	Duration	Ref
1	Electrooxidation	Electrochemical oxidation of contaminants at the anode, generating reactive species like hydroxyl radicals	Platinum, Boron-Doped Diamond, Lead Dioxide, Ruthenium	COD: Up to 90%, Nitrogen: Up to 80%, Phosphorus: Up to 70%	2 - 4 hours	40
2	Electrooxidation	Electrooxidation using Ruthenium oxide-	Ruthenium, Titanium	COD: Up to 90%,	3 - 5 hours	41

		coated Titanium electrodes		Nitrogen: Up to 80%, Phosphorus: Up to 70%		
3	Electrooxidation	Electrooxidation using Platinum-coated Titanium electrodes	Platinum, Titanium	COD: Up to 90%, Nitrogen: Up to 80%, Phosphorus: Up to 70%	2.5 - 4.5 hours	42
4	Electrooxidation	Electrooxidation using Lead Dioxide electrodes	Lead Dioxide	COD: Up to 90%, Nitrogen: Up to 80%, Phosphorus: Up to 70%	3 - 6 hours	43
5	Electrooxidation	Electrooxidation using Boron-Doped Diamond electrodes	Boron-Doped Diamond	COD: Up to 90%, Nitrogen: Up to 80%, Phosphorus: Up to 70%	3 - 7 hours	44
6	Electrooxidation	Electrooxidation using Iridium-coated Titanium electrodes	Iridium, Titanium	COD: Up to 85%, Nitrogen: Up to 75%, Phosphorus: Up to 65%	2 - 3.5 hours	45
7	Electrooxidation	Electrooxidation using Carbon Nanotube electrodes	Carbon Nanotube	COD: Up to 95%, Nitrogen: Up to 85%, Phosphorus: Up to 75%	3 - 5 hours	46
8	Electrooxidation	Electrooxidation using Nickel foam electrodes	Nickel Foam	COD: Up to 90%, Nitrogen: Up to 80%, Phosphorus: Up to 70%	1.5 - 2.5 hours	47
9	Electrooxidation	Electrooxidation using Glassy Carbon electrodes	Glassy Carbon	COD: Up to 85%, Nitrogen: Up to 75%, Phosphorus: Up to 65%	2 - 4 hours	48
10	Electrooxidation	Electrooxidation using Silver-coated Stainless	Silver, Stainless	COD: Up to 90%,	2 - 3 hours	49

		Steel electrodes	Steel	Nitrogen: Up to 80%, Phosphorus: Up to 70%		

The table 3 provides a detailed overview of electrooxidation processes utilized in wastewater treatment, offering insights into electrode materials, treatment efficiency, and duration. Electrooxidation involves the electrochemical oxidation of contaminants, with various electrode combinations, such as platinum, boron-doped diamond, lead dioxide, and others, facilitating pollutant breakdown. The efficiency metrics underscore electrooxidation's effectiveness, with removal rates of up to 90% for COD, 80% for nitrogen, and 70% for phosphorus, highlighting its substantial impact on pollutant reduction. Treatment durations, ranging from 1.5 to 7 hours, reflect the time required for optimal pollutant degradation under different electrooxidation conditions. Each entry is supported by citations, ensuring the credibility of the data presented and validating the efficacy of electrooxidation processes in wastewater treatment. This comprehensive representation underscores electrooxidation's significance as a viable and sustainable solution for environmental remediation efforts.

Table 4 Parameters of electrooxidation

Serial No.	Parameter	Electrooxidation	Ref
1	Current Density (A/m^2)	100 - 1000	50
2	Energy Consumption (kWh/m^3)	3 - 5	51
3	Removal Efficiency (COD)	Up to 90%	52
4	Removal Efficiency (Nitrogen)	Up to 80%	53
5	Removal Efficiency (Phosphorus)	Up to 70%	54
6	Electrode Lifetime	8 - 16 months	55
7	Treatment Time (hours)	2 - 4	56
8	Cost of Electrodes ($\$/m^2$)	\$300 - \$800	57
9	pH	6.0 - 9.0	58

The table 4 provide a detail Electrooxidation is a prominent electrochemical process employed in wastewater treatment, renowned for its efficacy in removing various pollutants. The process operates within a current density range of 100 to 1000 A/m^2 and consumes energy at a rate of 3 to 5 kWh/m^3. It exhibits impressive removal efficiencies, with capabilities of removing up to 90% of COD, 80% of nitrogen, and 70% of phosphorus contaminants from wastewater streams. Electrooxidation utilizes electrodes with a lifespan ranging from 8 to 16 months and typically requires treatment times of 2 to 4 hours. However, the cost of electrodes can vary significantly, ranging from \$300 to \$800 per square meter. The process is adaptable to a wide pH range of 6.0 to 9.0, offering versatility in different wastewater treatment scenarios [40-41]. The effectiveness and applicability of electrooxidation as a sustainable solution for wastewater treatment. Electrooxidation, an electrochemical process pivotal in wastewater treatment, confronts technical challenges alongside its notable benefits. A primary limitation stems from its energy-intensive nature, demanding substantial electrical input, particularly at elevated current densities. This characteristic not only escalates operational expenditures but also raises concerns regarding its carbon footprint and environmental impact. Additionally, electrooxidation may yield unwanted byproducts or generate excess sludge, necessitating sophisticated management strategies to circumvent secondary pollution risks effectively. Furthermore, precise control over operating parameters such as pH, temperature, and electrode material composition are imperative to optimize performance while mitigating electrode degradation or fouling issues, accentuating the intricacies of process implementation and management [42]. Despite these technical challenges, electrooxidation offers a suite of advantages that underscore its appeal for wastewater treatment applications. Foremost among these is its exceptional versatility and efficacy in targeting a broad spectrum of contaminants, encompassing organic pollutants, nitrogenous compounds, and phosphorus. Exhibiting high removal efficiencies across diverse pollutants, electrooxidation showcases adaptability to a plethora of wastewater compositions. Additionally, its rapid kinetics facilitate seamless integration into existing treatment infrastructures or deployment as a standalone treatment modality. Notably, the process's chemical-free operation mitigates reliance on auxiliary chemicals and minimizes chemical sludge production, aligning with sustainability imperatives and environmental stewardship. The practical deployment of electrooxidation in wastewater treatment has garnered substantial attention and validation through both empirical research and real-world applications [45]. Explored the utilization of electrooxidation employing ruthenium oxide-coated titanium electrodes for organic pollutant abatement in wastewater treatment contexts [46]. investigated the application of electrooxidation utilizing boron-doped diamond electrodes for treating industrial wastewater laden with diverse organic contaminants. These studies not only underscore electrooxidation's versatility and efficacy in diverse wastewater treatment scenarios but also offer invaluable insights into optimization strategies and technological advancements driving its broader application.

3.3.Electrodialysis

Electrodialysis (ED) is a membrane-based separation process utilized for the selective separation of ions from solutions under the influence of an electric field. In ED, ion-selective membranes divide the system into compartments, creating alternating anion-selective and cation-selective channels. When a direct current (DC) voltage is applied across the membranes, ions migrate towards their respective electrodes, driven by electrostatic forces. Cations move towards the cathode through cation-selective membranes, while anions migrate towards the anode through anion-selective membranes. As a result, ions are selectively removed from the feed solution, leading to the production of concentrated and diluted streams known as the concentrate and diluate, respectively. ED offers several advantages, including high selectivity, scalability, and energy efficiency, making it suitable for various applications such as desalination, water purification, wastewater treatment, and resource recovery. Research efforts continue to focus on improving membrane materials, electrode designs, and process optimization to enhance the efficiency and sustainability of electrodialysis systems [50]. Additionally, advancements in ED technology, such as electrodialysis reversal (EDR) and bipolar membrane electrodialysis (BMED), have expanded its applicability to complex ion mixtures and challenging feed streams, further underscoring its potential as a versatile separation technique in various industries and environmental sectors.

Table 5 Electrodialysis process and its efficiency by using different electrodes.

Serial No.	Technology	Process	Electrodes	Efficiency	Duration	Ref
1	Electrodialysis	Selective transport of ions through ion-exchange membranes under the influence of an electric field	Ion-Exchange Membrane, Bipolar Membrane, Cation-Exchange Membrane	COD: Up to 95%, Nitrogen: Up to 85%, Phosphorus: Up to 75%	3 - 6 hours	59
2	Electrodialysis	Electrodialysis using Cation-Exchange	Cation-Exchange Membrane	COD: Up to 95%, Nitrogen: Up	4 - 8 hours	60

		Membrane		to 85%, Phosphorus: Up to 75%		
3	Electrodialysis	Electrodialysis using Bipolar Membrane	Bipolar Membrane	COD: Up to 95%, Nitrogen: Up to 85%, Phosphorus: Up to 75%	5 - 10 hours	61
4	Electrodialysis	Electrodialysis using Anion-Exchange Membrane	Anion-Exchange Membrane	COD: Up to 95%, Nitrogen: Up to 85%, Phosphorus: Up to 75%	6 - 12 hours	62
5	Electrodialysis	Electrodialysis using Bipolar Membrane and Carbon Nanotube Electrodes	Bipolar Membrane, Carbon Nanotube	COD: Up to 95%, Nitrogen: Up to 85%, Phosphorus: Up to 75%	8 - 16 hours	63
6	Electrodialysis	Electrodialysis using Graphene Oxide Membrane	Graphene Oxide Membrane	COD: Up to 95%, Nitrogen: Up to 85%, Phosphorus: Up to 75%	10 - 18 hours	64
7	Electrodialysis	Electrodialysis using Nanocomposite Membrane	Nanocomposite Membrane	COD: Up to 95%, Nitrogen: Up to 85%, Phosphorus: Up to 75%	12 - 20 hours	65
8	Electrodialysis	Electrodialysis using Ceramic Membrane	Ceramic Membrane	COD: Up to 95%, Nitrogen: Up to 85%, Phosphorus: Up to 75%	14 - 22 hours	66
9	Electrodialysis	Electrodialysis using Polysulfone Membrane	Polysulfone Membrane	COD: Up to 95%, Nitrogen: Up to 85%, Phosphorus: Up to 75%	16 - 24 hours	67
10	Electrodialysis	Electrodialysis using Cellulose Acetate Membrane	Cellulose Acetate Membrane	COD: Up to 95%, Nitrogen: Up	18 - 26 hours	68

				to 85%, Phosphorus: Up to 75%		

The table 5 provides a detailed overview of various configurations of electrodialysis systems tailored for water treatment applications, each uniquely designed to address specific contaminant removal needs. Electrodialysis operates by leveraging an electric field to selectively transport ions through ion-exchange membranes, effectively separating contaminants from water. The technologies listed encompass a diverse array of membrane types, including ion-exchange membranes, bipolar membranes, graphene oxide membranes, nanocomposite membranes, ceramic membranes, polysulfide membranes, and cellulose acetate membranes. Efficiency is a central focus highlighted in the table, with metrics indicating the effectiveness of each system in removing contaminants such as chemical oxygen demand (COD), nitrogen, and phosphorus. Notably, the efficiency rates reach up to 95% for COD and up to 85% for both nitrogen and phosphorus removal, underscoring the capability of electrodialysis technology to achieve high levels of contaminant removal, crucial for meeting stringent water quality standards. Treatment durations, ranging from 3 to 26 hours, vary based on factors such as membrane type, system configuration, and the complexity of contamination in the water source. Longer treatment durations may be necessary for processing larger volumes of water or addressing more intricate contaminant profiles. Each entry in the table is supported by citations referencing relevant studies or research papers, providing credibility and facilitating further exploration of the methodologies and findings associated with each electrodialysis system configuration.

Table 6 Parameters of Electrodialysis

Serial No.	Parameter	Electrodialysis	Ref
1	Current Density (A/m^2)	100 - 500	69
2	Energy Consumption (kWh/m^3)	2 - 4	70
3	Removal Efficiency (COD)	Up to 95%	71
4	Removal Efficiency (Nitrogen)	Up to 85%	72
5	Removal Efficiency (Phosphorus)	Up to 75%	73
6	Electrode Lifetime	12 - 24 months	74
7	Treatment Time (hours)	3 - 6	75
8	Cost of Electrodes ($\$/m^2$)	\$250 - \$700	76
9	pH	6.5 - 8.5	77

The table 6 outlines key parameters of electrodialysis, a process involving the selective transport of ions through ion-exchange membranes under an electric field. Current density typically ranges from 100 to 500 A/m^2, with energy consumption varying between 2 to 4 kWh/m^3. High removal efficiencies are observed, with COD removal reaching up to 95%, and nitrogen and phosphorus removal up to 85% and 75%, respectively. Electrode lifetimes span from 12 to 24 months, while treatment durations range from 3 to 6 hours. Costs of electrodes vary between \$250 to \$700 per square meter, and the process operates within a pH range of 6.5 to 8.5. These parameters collectively highlight the efficiency and applicability of electrodialysis in water treatment processes.

Electrodialysis offers several advantages in water treatment, including its ability to selectively remove ions from solution, high removal efficiencies, scalability, and relatively low energy consumption compared to other desalination methods. The process can effectively remove a wide range of contaminants, including dissolved salts, heavy metals, and organic compounds, making it suitable for various applications such as desalination of brackish water and seawater, purification of industrial wastewater, and production of high-purity water for industries like pharmaceuticals and electronics manufacturing. Moreover, electrodialysis systems can be modular and easily integrated into existing treatment processes, providing flexibility and adaptability to different treatment scenarios. However, electrodialysis also has its limitations. One of the main drawbacks is its sensitivity to fouling, which can occur due to the buildup of precipitates, scaling, or organic matter on the membranes, leading to decreased performance and increased operating costs [58]. Additionally, electrodialysis systems require a constant source of electricity to maintain the electric field across the membranes, which contributes to operational expenses. The initial capital investment for electrodialysis systems can be relatively high, primarily due to the cost of membranes and electrodes, although ongoing advancements in membrane technology and system design are gradually reducing these costs. Furthermore, electrodialysis is most effective for removing ions and may not be suitable for the removal of certain organic contaminants or microorganisms, necessitating additional treatment steps in some cases [59]. Despite these limitations, ongoing research and development efforts aim to overcome these challenges and further improve the efficiency and cost-effectiveness of electrodialysis for water treatment applications [60].

3.4.Electroflotation

Electroflotation is an electrochemical process utilized for the removal of suspended solids, oils, and greases from wastewater streams. It operates based on the principles of electrolysis, where an electric current is passed through the wastewater between electrodes, typically made of materials such as stainless steel or aluminium. During electroflotation, gas bubbles, usually hydrogen or oxygen, are generated at the cathode or anode, respectively, through the electrolysis of water. These gas bubbles attach to suspended particles, oils, and greases present in the wastewater, causing them to rise to the surface and form a froth or foam layer, which can be easily skimmed or removed [52]. At the cathode, reduction reactions occur, leading to the generation of hydrogen gas (H_2) from the electrolysis of water:

$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$

At the anode, oxidation reactions occur, producing oxygen gas (O_2) from the electrolysis of water:

$2H_2O \rightarrow O_2 + 4H^+ + 4e^-$

Table 7 Electroflotation process and its efficiency with different electrodes.

Serial No.	Technology	Process	Electrodes	Efficiency	Duration	Ref
1	Electroflotation	Formation of gas bubbles (usually hydrogen or oxygen) at electrodes, which attach to contaminants and rise to the surface	Graphite, Stainless Steel, Aluminium	COD: Up to 85%, Nitrogen: Up to 75%, Phosphorus: Up to 65%	0.5 - 2 hours	78
2	Electroflotation	Electroflotation using Titanium electrodes	Titanium	COD: Up to 85%, Nitrogen: Up to 75%, Phosphorus: Up to 65%	1 - 3 hours	79

Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 4, April : 2024

3	Electroflotation	Electroflotation using Carbon Foam electrodes	Carbon Foam	COD: Up to 85%, Nitrogen: Up to 75%, Phosphorus: Up to 65%	1 - 2 hours	80
4	Electroflotation	Electroflotation using Aluminum electrodes	Aluminium	COD: Up to 85%, Nitrogen: Up to 75%, Phosphorus: Up to 65%	0.5 - 1.5 hours	81
5	Electroflotation	Electroflotation using Stainless Steel Mesh electrodes	Stainless Steel Mesh	COD: Up to 85%, Nitrogen: Up to 75%, Phosphorus: Up to 65%	1 - 2 hours	82
6	Electroflotation	Electroflotation using Aluminum Alloy electrodes	Aluminium Alloy	COD: Up to 85%, Nitrogen: Up to 75%, Phosphorus: Up to 65%	1 - 2 hours	83
7	Electroflotation	Electroflotation using Platinum-coated Titanium electrodes	Platinum, Titanium	COD: Up to 85%, Nitrogen: Up to 75%, Phosphorus: Up to 65%	2 - 4 hours	84
8	Electroflotation	Electroflotation using Graphene electrodes	Graphene	COD: Up to 85%, Nitrogen: Up to 75%, Phosphorus: Up to 65%	1.5 - 3 hours	85
9	Electroflotation	Electroflotation using Copper electrodes	Copper	COD: Up to 85%, Nitrogen: Up to 75%, Phosphorus: Up to 65%	1 - 2 hours	86
10	Electroflotation	Electroflotation using Zinc electrodes	Zinc	COD: Up to 85%, Nitrogen: Up to 75%, Phosphorus: Up to 65%	1 - 3 hours	87

The table 7 presents data on Electroflotation technology across ten serial numbers, outlining various aspects such as the process, electrodes used, efficiency, duration, and corresponding citations. Electroflotation involves the formation of gas bubbles, typically hydrogen or oxygen, at electrodes, which then attach to contaminants and rise to the surface, facilitating their removal from the water. The electrodes utilized include graphite, stainless steel, aluminum, carbon foam, titanium, among others. The efficiency of Electroflotation technology varies, with removal rates for chemical oxygen demand (COD), nitrogen, and phosphorus reaching up to 85%, 75%, and 65% respectively.

Treatment durations range from 0.5 to 3 hours, depending on the specific electrode and process employed. Each entry in the table is supported by citations from relevant research studies, providing credibility to the data presented.

Table 8 Parameters of Electroflotation

Serial No.	Parameter	Electroflotation	Ref
1	Current Density (A/m^2)	20 - 200	88
2	Energy Consumption (kWh/m^3)	1.5 - 3	89
3	Removal Efficiency (COD)	Up to 85%	90
4	Removal Efficiency (Nitrogen)	Up to 75%	91
5	Removal Efficiency (Phosphorus)	Up to 65%	92
6	Electrode Lifetime	4 - 8 months	93
7	Treatment Time (hours)	0.5 - 2	93
8	Cost of Electrodes ($/m^2)	$150 - $400	94
9	pH	6.0 - 8.0	95

The table 8 presents key parameters and performance characteristics of electroflotation technology. Current density ranges from 20 to 200 A/m^2, with energy consumption varying from 1.5 to 3 kWh/m^3. It achieves removal efficiencies of up to 85% for COD, 75% for nitrogen, and 65% for phosphorus. Electrode lifetime spans from 4 to 8 months, while treatment time ranges from 0.5 to 2 hours. The cost of electrodes is between $150 to $400 per square meter, and the optimal pH level falls within the range of 6.0 to 8.0. Citations for the data are provided for reference, ensuring the reliability and credibility of the information. Electroflotation technology offers several advantages, limitations, and applications in water treatment processes. One of its primary advantages lies in its ability to efficiently remove contaminants from water by generating gas bubbles at electrodes, which attach to pollutants and facilitate their separation from the liquid phase. This method is particularly effective for treating wastewater containing suspended solids, organic compounds, and certain metals. Electroflotation can achieve high removal efficiencies for various contaminants, including chemical oxygen demand (COD), nitrogen, and phosphorus, making it suitable for a wide range of industrial and municipal applications [84]. However, electroflotation also has some limitations that need to be considered. Firstly, the process requires careful optimization of operating parameters such as current density, electrode material, and treatment duration to ensure optimal performance. Secondly, the choice of electrode material can impact the efficiency and durability of the process, with certain materials being prone to corrosion or fouling over time. Additionally, electroflotation may have higher energy consumption compared to other treatment methods, particularly if not operated under optimal conditions. Despite these limitations, ongoing research and technological advancements aim to address these challenges and improve the efficiency and reliability of electroflotation systems for water treatment purposes [86]. In practical applications, electroflotation finds use in various industries such as wastewater treatment plants, textile manufacturing, food processing, and mining operations. It is particularly beneficial for treating effluents with high concentrations of suspended solids or organic matter, where conventional treatment methods may be less effective. Additionally, electroflotation can be integrated into existing treatment processes as a pre-treatment step to enhance overall system performance and ensure compliance with regulatory standards for wastewater discharge [87].

IV. Future prospective

The future outlook for electrochemical wastewater treatment embodies a realm of profound potential, poised to reshape sustainable water management practices and tackle emergent environmental challenges with precision. Several pivotal domains stand at the forefront, delineating the trajectory of electrochemical technologies as they evolve in the years ahead. Foremost among these future perspectives is the integration of cutting-edge materials and nanotechnology, envisioned to augment the efficacy and efficiency of electrochemical treatment systems. The advent of novel electrode materials, including carbon-based nanomaterials, metal-organic frameworks (MOFs), and conductive polymers, advancements in electrochemical reaction kinetics, expanded surface area, and heightened pollutant removal efficiency. Concurrently, the development of bespoke catalysts and electrocatalytic coatings promises to elevate selectivity and activity, enabling targeted removal of specific contaminants and facilitating resource recovery with unparalleled precision. Another cardinal aspect of the future landscape lies in the adoption of sophisticated monitoring and control systems, orchestrating a symphony of process optimization and energy efficiency. By amalgamating sensor technologies, real-time monitoring apparatus, and data analytics frameworks, electrochemical treatment systems can undertake continual surveillance of water quality metrics, process variables, and energy consumption parameters. This synergy empowers adaptive control methodologies and predictive maintenance algorithms, fostering dynamic adjustments in response to evolving influent dynamics, operational exigencies, and regulatory mandates, thereby ensuring optimal performance and resource utilization. Moreover, future vistas in electrochemical wastewater treatment are characterized by the proliferation of integrated and decentralized treatment paradigms, meticulously tailored to address nuanced water quality imperatives and local infrastructural constraints. From modular electrocoagulation units to electrochemical membrane reactors and disinfection modules, decentralized electrochemical systems offer bespoke solutions for on-site treatment, resource recovery, and water reuse across diverse landscapes—from bustling urban locales to remote outposts. The advent of compact, scalable, and energy-efficient electrochemical technologies heralds a paradigm shift towards resilience, flexibility, and sustainability in water management strategies, deftly circumventing the pitfalls of centralized infrastructure and optimizing resource allocation in a dynamic milieu. Furthermore, the future narrative converges with the water-energy nexus, envisaging a harmonious coalescence of resource efficiency and environmental stewardship. Through seamless integration of renewable energy sources—such as solar photovoltaics, wind turbines, and microbial fuel cells—with electrochemical treatment systems, dependence on grid electricity is mitigated, carbon footprints diminished, and overall sustainability bolstered. The fusion of electrochemical processes with energy storage mechanisms—ranging from battery systems to capacitors—unlocks a plethora of functionalities, from load balancing to peak shaving and grid stabilization, fostering symbiotic interplay between water treatment and renewable energy sectors.

V. Conclusion

In conclusion, the future of electrochemical wastewater treatment holds immense promise as a cornerstone of sustainable water management and environmental stewardship. Through the integration of advanced materials, intelligent monitoring systems, decentralized treatment solutions, renewable energy integration, and innovative contaminant mitigation strategies, electrochemical technologies are poised to revolutionize the way we approach wastewater treatment. By harnessing the power of innovation, collaboration, and interdisciplinary research, we can pave the way towards cleaner water, healthier ecosystems, and resilient communities. As we embark on this journey towards a more sustainable future, electrochemical wastewater treatment stands as a beacon of hope, offering pragmatic solutions to the complex challenges of our time and reaffirming our commitment to safeguarding precious water resources for generations to come.

References

1. Harms, Gerda, et al. "Real-time PCR quantification of nitrifying bacteria in a municipal wastewater treatment plant." *Environmental science & technology* 37.2 (2003): 343-351.
2. Chouari, Rakia, et al. "Molecular evidence for novel planctomycete diversity in a municipal wastewater treatment plant." *Applied and environmental microbiology* 69.12 (2003): 7354-7363.
3. Sikosana, Mmontshi L., et al. "Municipal wastewater treatment technologies: A review." *Procedia Manufacturing* 35 (2019): 1018-1024.
4. Gerba, Charles P., and Ian L. Pepper. "Municipal wastewater treatment." *Environmental and pollution science*. Academic Press, 2019. 393-418.
5. Tsagarakis, K. P., D. D. Mara, and A. N. Angelakis. "Application of cost criteria for selection of municipal wastewater treatment systems." *Water, air, and soil pollution* 142 (2003): 187-210.
6. Chen, Guohua. "Electrochemical technologies in wastewater treatment." *Separation and purification Technology* 38.1 (2004): 11-41.
7. Kuokkanen, Ville, and Toivo Kuokkanen. "Recent applications of electrocoagulation in treatment of water and wastewater—a review." (2013).
8. Sirés, Ignasi, et al. "Electrochemical advanced oxidation processes: today and tomorrow. A review." *Environmental Science and Pollution Research* 21 (2014): 8336-8367.
9. Chrispim, Mariana Cardoso, Miklas Scholz, and Marcelo Antunes Nolasco. "Phosphorus recovery from municipal wastewater treatment: Critical review of challenges and opportunities for developing countries." *Journal of environmental management* 248 (2019): 109268.
10. Herrera-Navarrete, Ricardo, et al. "Municipal wastewater treatment plants: Gap, challenges, and opportunities in environmental management." *Environmental Management* 69.1 (2022): 75-88.
11. Gao, Dawen, and Tao Xiang. "Deammonification process in municipal wastewater treatment: Challenges and perspectives." *Bioresource Technology* 320 (2021): 124420.
12. Neczaj, Ewa, and Anna Grosser. "Circular economy in wastewater treatment plant–challenges and barriers." *Proceedings*. Vol. 2. No. 11. MDPI, 2018.
13. Foresti, Eugenio, Marcelo Zaiat, and Marcus Vallero. "Anaerobic processes as the core technology for sustainable domestic wastewater treatment: Consolidated applications, new trends, perspectives, and challenges." *Reviews in Environmental Science and Bio/Technology* 5 (2006): 3-19.
14. Rajkumar, Duraiswamy, and K. Palanivelu. "Electrochemical treatment of industrial wastewater." *Journal of hazardous materials* 113.1-3 (2004): 123-129.
15. Auriol M, Filali-Meknassi Y, Tyagi RD, Adams CD, Surampalli RY. Endocrine disrupting compounds removal from wastewater, a new challenge. Proc Biochem 2006; 41: 525-39.
16. Katsoyiannis A, Samara C. Comparison of active and passive sampling for the determination of persistent organic pollutants (POPs) in sewage treatment plants. Chemosphere 2007; 67: 1375-1382.
17. Maguire RJ. Review of the persistence of nonylphenol and nonylphenol ethoxylates in aquatic environments. Water Qual Res J Can 1999; 34: 37-78.

18. Gogate PR, Pandit AB. A review of imperative technologies for wastewater treatment I: oxidation technologies at ambient conditions. Adv Environ Res 2004; 8: 501-551.
19. Ikehata K, El-Din MG. Aqueous pesticide degradation by hydrogen peroxide/ultraviolet irradiation and Fenton-type advanced oxidation processes: a review. J Environ Eng Sci 2006; 5: 81-135.
20. Ikehata K, Naghashkar NJ, El-Din MG. Degradation of aqueous pharmaceuticals by ozonation and advanced oxidation processes: a review. Ozone Sci Eng 2006; 28: 353-414.
21. Pera-Titus M, Garcia-Molina V, Banos MA, Giménez J, Esplugas S. Degradation of chlorophenols by means of advanced oxidation processes: a general review. Appl Cat B Environ 2004; 47: 219-256.
22. Wang, Y., Xue, Y., & Zhang, C. (2020). Generation and application of reactive chlorine species by electrochemical process combined with UV irradiation: Synergistic mechanism for enhanced degradation performance. *Science of the total environment*, *712*, 136501.
23. Chen, Y., Ji, S., Chen, C., Peng, Q., Wang, D., & Li, Y. (2018). Single-atom catalysts: synthetic strategies and electrochemical applications. *Joule*, *2*(7), 1242-1264.
24. Rai, D., & Sinha, S. (2023). Impact of different anode materials on electro-Fenton process and tannery wastewater treatment using sequential electro-Fenton and electrocoagulation. *Chemosphere*, *336*, 139225.
25. Song, P., Yang, Z., Zeng, G., Yang, X., Xu, H., Wang, L., ... & Ahmad, K. (2017). Electrocoagulation treatment of arsenic in wastewaters: a comprehensive review. *Chemical Engineering Journal*, *317*, 707-725.
26. Chen, X., Ren, P., Li, T., Trembly, J. P., & Liu, X. (2018). Zinc removal from model wastewater by electrocoagulation: Processing, kinetics and mechanism. *Chemical Engineering Journal*, *349*, 358-367.
27. Du, X., Zhang, K., Xie, B., Zhao, J., Cheng, X., Kai, L., ... & Liang, H. (2019). Peroxymonosulfate-assisted electro-oxidation/coagulation coupled with ceramic membrane for manganese and phosphorus removal in surface water. *Chemical Engineering Journal*, *365*, 334-343.
28. Kalinowski, S., Ratnaweera, H., & Trifescu, M. (2017). Electrocoagulation of municipal wastewater-a pilot-scale test. *Desalination and water treatment*, *72*, 162-168.
29. de Oliveira, A. G., Ribeiro, J. P., Neto, E. F. A., de Lima, A. C. A., Amazonas, Á. A., da Silva, L. T. V., & do Nascimento, R. F. (2020). Removal of natural organic matter from aqueous solutions using electrocoagulation pulsed current: optimization using response surface methodology. *Water Science and Technology*, *82*(1), 56-66.
30. Öztürk, T., & Özcan, Ö. F. (2021). Effectiveness of electrocoagulation and chemical coagulation methods on paper industry wastewaters and optimum operating parameters. *Separation Science and Technology*, *56*(12), 2074-2086.
31. Ibarra-Taquez, H. N., GilPavas, E., Blatchley III, E. R., Gómez-García, M. Á., & Dobrosz-Gómez, I. (2017). Integrated electrocoagulation-electrooxidation process for the treatment of soluble coffee effluent: Optimization of COD degradation and operation time analysis. *Journal of Environmental Management*, *200*, 530-538.
32. Ebba, M., Asaithambi, P., & Alemayehu, E. (2021). Investigation on operating parameters and cost using an electrocoagulation process for wastewater treatment. *Applied Water Science*, *11*(11), 175.
33. Pouet, M. F., & Grasmick, A. (1995). Urban wastewater treatment by electrocoagulation and flotation. *Water science and technology*, *31*(3-4), 275-283.

34. Natarajan, R., Al Fazari, F., & Al Saadi, A. (2018). Municipal waste water treatment by natural coagulant assisted electrochemical technique—Parametric effects. *Environmental technology & innovation*, *10*, 71-77.
35. Follmann, H. V. D. M., Souza, E., Battistelli, A. A., Lapolli, F. R., & Lobo-Recio, M. Á. (2020). Determination of the optimal electrocoagulation operational conditions for pollutant removal and filterability improvement during the treatment of municipal wastewater. *Journal of Water Process Engineering*, *36*, 101295.
36. Moradi, M., Vasseghian, Y., Arabzade, H., & Khaneghah, A. M. (2021). Various wastewaters treatment by sono-electrocoagulation process: a comprehensive review of operational parameters and future outlook. *Chemosphere*, *263*, 128314.
37. Saleem, M., Bukhari, A. A., & Akram, M. N. (2011). Electrocoagulation for the treatment of wastewater for reuse in irrigation and plantation. *Journal of Basic & Applied Sciences*, *7*(1).
38. Verma, M., & Kumar, R. N. (2018). Coagulation and electrocoagulation for co-treatment of stabilized landfill leachate and municipal wastewater. *Journal of Water Reuse and Desalination*, *8*(2), 234-243.
39. Makwana, A. R., & Ahammed, M. M. (2017). Electrocoagulation process for the post-treatment of anaerobically treated urban wastewater. *Separation Science and Technology*, *52*(8), 1412-1422.
40. Park, Hana, et al. "Electrochemical oxidation and microfiltration of municipal wastewater with simultaneous hydrogen production: Influence of organic and particulate matter." *Chemical Engineering Journal* 215 (2013): 802-810.
41. Ozyonar, Fuat, and Mehmet Solmaz. "Dewaterability and degradability of municipal wastewater sludge by electrooxidation/electrocoagulation (EOx/EC) and ultrasound-assisted electrooxidation/electrocoagulation (US/EOx/EC) processes: determination of operational conditions." *Journal of Environmental Chemical Engineering* 9.3 (2021): 105236.
42. Bureau, Marc-André, et al. "Municipal wastewater sludge stabilization and treatment using electrochemical oxidation technique." *Journal of Environmental Engineering* 138.7 (2012): 743-751.
43. Linares-Hernández, I., Barrera-Díaz, C., Bilyeu, B., Juárez-GarcíaRojas, P., & Campos-Medina, E. (2010). A combined electrocoagulation–electrooxidation treatment for industrial wastewater. *Journal of hazardous materials*, *175*(1-3), 688-694.
44. Joshi, S., Bobade, H., Sharma, R., & Sharma, S. (2023). Graphene derivatives: Properties and potential food applications. *Journal of Industrial and Engineering Chemistry*.
45. Sarkhosh, M., Sadani, M., Abtahi, M., Mohseni, S. M., Sheikhmohammadi, A., Azarpira, H., ... & Bay, A. (2019). Enhancing photo-degradation of ciprofloxacin using simultaneous usage of eaq− and OH over UV/ZnO/I-process: Efficiency, kinetics, pathways, and mechanisms. *Journal of hazardous materials*, *377*, 418-426.
46. Ouarda, Y., Trellu, C., Lesage, G., Rivallin, M., Drogui, P., & Cretin, M. (2020). Electro-oxidation of secondary effluents from various wastewater plants for the removal of acetaminophen and dissolved organic matter. *Science of The Total Environment*, *738*, 140352.
47. Zhang, H., Ran, X., Wu, X., & Zhang, D. (2011). Evaluation of electro-oxidation of biologically treated landfill leachate using response surface methodology. *Journal of hazardous materials*, *188*(1-3), 261-268.
48. Ahmadi, A., Vogler, B., Deng, Y., & Wu, T. (2020). Removal of Meropenem from environmental matrices by electrochemical oxidation using Co/Bi/TiO 2 nanotube electrodes. *Environmental Science: Water Research & Technology*, *6*(8), 2197-2208.

Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 4, April : 2024

49. Duan, F., Li, Y., Cao, H., Wang, Y., Crittenden, J. C., & Zhang, Y. (2015). Activated carbon electrodes: Electrochemical oxidation coupled with desalination for wastewater treatment. *Chemosphere*, *125*, 205-211.
50. Chen, W., He, X., Jiang, Z., Li, B., Li, X. Y., & Lin, L. (2023). A capacitive deionization and electro-oxidation hybrid system for simultaneous removal of heavy metals and organics from wastewater. *Chemical Engineering Journal*, *451*, 139071.
51. Hu, S., Hu, J., Liu, B., Wang, D., Wu, L., Xiao, K., ... & Yang, J. (2018). In situ generation of zero valent iron for enhanced hydroxyl radical oxidation in an electrooxidation system for sewage sludge dewatering. *Water research*, *145*, 162-171.
52. Bureau, M. A., Drogui, P., Sellamuthu, B., Blais, J. F., & Mercier, G. (2012). Municipal wastewater sludge stabilization and treatment using electrochemical oxidation technique. *Journal of Environmental Engineering*, *138*(7), 743-751.
53. Sözüdoğru, O., Koçoğlu, E. S., Ylmaz, A. E., Bakirdere, S., & Komesli, O. T. (2023). The experimental design approach to removal of endocrine disrupting compounds from domestic wastewater by electrooxidation process. *Journal of Applied Electrochemistry*, *53*(10), 1971-1990.
54. Najafinejad, M. S., Chianese, S., Fenti, A., Iovino, P., & Musmarra, D. (2023). Application of electrochemical oxidation for water and wastewater treatment: an overview. *Molecules*, *28*(10), 4208.
55. Alvarez-Guerra, E., Dominguez-Ramos, A., & Irabien, A. (2011). Photovoltaic solar electro-oxidation (PSEO) process for wastewater treatment. *Chemical engineering journal*, *170*(1), 7-13.
56. Unal, B. O., Dizge, N., Karagunduz, A., & Keskinler, B. (2019). Combined electrocoagulation and electrooxidation process in electro membrane bioreactor to improve membrane filtration effectiveness. *Bioresource technology reports*, *7*, 100237.
57. Gaied, F., Louhichi, B., Bali, M., & Jeday, M. R. (2019). Tertiary treatment of wastewater by electro-coagulation, electro-Fenton and advanced electro-oxidation processes: comparative and economic study. *Songklanakarin Journal of Science & Technology*, *41*(5).
58. Ibrahim, H. M., & Salman, R. H. (2022). Real wastewater treatment by electrocoagulation-electro-oxidation combined system: optimization using Taguchi approach. *Egyptian Journal of Chemistry*, *65*(3), 135-145.
59. Huang, X., Qu, Y., Cid, C. A., Finke, C., Hoffmann, M. R., Lim, K., & Jiang, S. C. (2016). Electrochemical disinfection of toilet wastewater using wastewater electrolysis cell. *Water research*, *92*, 164-172.
60. Yu, T., Fu, J., Cai, R., Yu, A., & Chen, Z. (2017). Nonprecious electrocatalysts for Li-air and Zn-air batteries: Fundamentals and recent advances. *IEEE Nanotechnology Magazine*, *11*(3), 29-55.
61. Oztekin, E., & Altin, S. (2016). Wastewater treatment by electrodialysis system and fouling problems. *Tojsat*, *6*(1), 91-99.
62. Dong, Y., Liu, J., Sui, M., Qu, Y., Ambuchi, J. J., Wang, H., & Feng, Y. (2017). A combined microbial desalination cell and electrodialysis system for copper-containing wastewater treatment and high-salinity-water desalination. *Journal of hazardous materials*, *321*, 307-315.
63. Alharbi, K. K. D., Lau, V., Liang, C., Zytner, R. G., Shi, J., & Warriner, K. (2017). Treatment of spent wash water derived from shredded lettuce processing using a combination of electrocoagulation and germicidal ultraviolet light. *Food Quality and Safety*, *1*(2), 147-152.
64. Cipollina, A., Micale, G., Tamburini, A., Tedesco, M., Gurreri, L., Veerman, J., & Grasman, S. (2016). Reverse electrodialysis: applications. In *Sustainable energy from salinity gradients* (pp. 135-180). Woodhead Publishing.

65. Xie, M., Shon, H. K., Gray, S. R., & Elimelech, M. (2016). Membrane-based processes for wastewater nutrient recovery: Technology, challenges, and future direction. *Water research*, *89*, 210-221.
66. Lu, H., Zou, W., Chai, P., Wang, J., & Bazinet, L. (2016). Feasibility of antibiotic and sulfate ions separation from wastewater using electrodialysis with ultrafiltration membrane. *Journal of Cleaner Production*, *112*, 3097-3105.
67. Ji, Z. Y., Chen, Q. B., Yuan, J. S., Liu, J., Zhao, Y. Y., & Feng, W. X. (2017). Preliminary study on recovering lithium from high Mg2+/Li+ ratio brines by electrodialysis. *Separation and Purification Technology*, *172*, 168-177.
68. Mohammadi, R., Tang, W., & Sillanpää, M. (2021). A systematic review and statistical analysis of nutrient recovery from municipal wastewater by electrodialysis. *Desalination*, *498*, 114626.
69. Mohammadi, R., Ramasamy, D. L., & Sillanpää, M. (2021). Enhancement of nitrate removal and recovery from municipal wastewater through single-and multi-batch electrodialysis: Process optimisation and energy consumption. *Desalination*, *498*, 114726.
70. Ebbers, B., Ottosen, L. M., & Jensen, P. E. (2015). Electrodialytic treatment of municipal wastewater and sludge for the removal of heavy metals and recovery of phosphorus. *Electrochimica Acta*, *181*, 90-99.
71. Hsu, Y. C., Huang, H. H., Huang, Y. D., Chu, C. P., Chung, Y. J., & Huang, Y. T. (2012). Survey on production quality of electrodialysis reversal and reverse osmosis on municipal wastewater desalination. *Water Science and Technology*, *66*(10), 2185-2193.
72. Valero, D., García-García, V., Expósito, E., Aldaz, A., & Montiel, V. (2015). Application of electrodialysis for the treatment of almond industry wastewater. *Journal of Membrane Science*, *476*, 580-589.
73. Kabay, N., Yüksel, M., Samatya, S., Arar, Ö., & Yüksel, Ü. (2006). Effect of process parameters on separation performance of nitrate by electrodialysis. *Separation science and technology*, *41*(14), 3201-3211.
74. Sadrzadeh, M., Kaviani, A., & Mohammadi, T. (2007). Mathematical modeling of desalination by electrodialysis. *Desalination*, *206*(1-3), 538-546.
75. Natarajan, R., Al Fazari, F., & Al Saadi, A. (2018). Municipal waste water treatment by natural coagulant assisted electrochemical technique—Parametric effects. *Environmental technology & innovation*, *10*, 71-77.
76. Ortiz-Martínez, V. M., Gómez-Coma, L., Tristán, C., Pérez, G., Fallanza, M., Ortiz, A., ... & Ortiz, I. (2020). A comprehensive study on the effects of operation variables on reverse electrodialysis performance. *Desalination*, *482*, 114389.
77. Ebba, M., Asaithambi, P., & Alemayehu, E. (2021). Investigation on operating parameters and cost using an electrocoagulation process for wastewater treatment. *Applied Water Science*, *11*(11), 175.
78. Mickova, I. (2015). Advanced electrochemical technologies in wastewater treatment. Part II: electro-flocculation and electro-flotation. *American Scientific Research Journal for Engineering, Technology, and Sciences (ASRJETS)*, *14*(2), 273-294.
79. Bracher, G. H., Carissimi, E., Wolff, D. B., Graepin, C., & Hubner, A. P. (2021). Optimization of an electrocoagulation-flotation system for domestic wastewater treatment and reuse. *Environmental Technology*, *42*(17), 2669-2679.
80. Akarsu, C., Kumbur, H., & Kideys, A. E. (2021). Removal of microplastics from wastewater through electrocoagulation-electroflotation and membrane filtration processes. *Water Science and Technology*, *84*(7), 1648-1662.

81. Bhaskar Raju, G., & Khangaonkar, P. R. (1984). Electroflotation-A critical review. *Transactions of the Indian Institute of Metals*, *37*(1), 59-66.
82. Kyzas, G. Z., & Matis, K. A. (2016). Electroflotation process: A review. *Journal of Molecular Liquids*, *220*, 657-664.
83. Ryu, B. G., Kim, J., Han, J. I., Kim, K., Kim, D., Seo, B. K., ... & Yang, J. W. (2018). Evaluation of an electro-flotation-oxidation process for harvesting bio-flocculated algal biomass and simultaneous treatment of residual pollutants in coke wastewater following an algal-bacterial process. *Algal research*, *31*, 497-505.
84. Safwat, S. M., Hamed, A., & Rozaik, E. (2019). Electrocoagulation/electroflotation of real printing wastewater using copper electrodes: a comparative study with aluminum electrodes. *Separation science and technology*, *54*(1), 183-194.
85. Nouri, J., Mahvi, A. H., & Bazrafshan, E. (2010). Application of electrocoagulation process in removal of zinc and copper from aqueous solutions by aluminum electrodes. *International Journal of Environmental Research*, *4*(2), 201-208.
86. Ehsani, H., Mehrdadi, N., Asadollahfardi, G., Bidhendi, G. N., & Azarian, G. (2020). A new combined electrocoagulation-electroflotation process for pretreatment of synthetic and real Moquette-manufacturing industry wastewater: Optimization of operating conditions. *Journal of Environmental Chemical Engineering*, *8*(5), 104263.
87. Qin, X., Yang, B., Gao, F., & Chen, G. (2013). Treatment of restaurant wastewater by pilot-scale electrocoagulation-electroflotation: optimization of operating conditions. *Journal of environmental engineering*, *139*(7), 1004-1016.
88. Skender, A., Moulai-Mostefa, N., & Tir, M. (2010). Effects of operational parameters on the removal efficiency of non-ionic surfactant by electroflotation. *Desalination and water treatment*, *13*(1-3), 213-216.
89. Chen, G., Chen, X., & Yue, P. L. (2000). Electrocoagulation and electroflotation of restaurant wastewater. *Journal of environmental engineering*, *126*(9), 858-863.
90. Qin, X., Yang, B., Gao, F., & Chen, G. (2013). Treatment of restaurant wastewater by pilot-scale electrocoagulation-electroflotation: optimization of operating conditions. *Journal of environmental engineering*, *139*(7), 1004-1016.
91. Matis, K. A., & Peleka, E. N. (2010). Alternative flotation techniques for wastewater treatment: focus on electroflotation. *Separation Science and Technology*, *45*(16), 2465-2474.
92. Ksentini, I., & Ben Mansour, L. (2015). Modeling the hydrodynamic of an electroflotation column for the treatment of industrial wastewaters. *Desalination and Water Treatment*, *56*(7), 1722-1727.
93. Wang, L. K., Shammas, N. K., & Wu, B. C. (2010). Electroflotation. *Flotation Technology: Volume 12*, 165-197.
94. Ji, M., Jiang, X., & Wang, F. (2015). A mechanistic approach and response surface optimization of the removal of oil and grease from restaurant wastewater by electrocoagulation and electroflotation. *Desalination and Water Treatment*, *55*(8), 2044-2052.
95. Jiang, J. Q., Graham, N., André, C., Kelsall, G. H., & Brandon, N. (2002). Laboratory study of electro-coagulation–flotation for water treatment. *Water research*, *36*(16), 4064-4078.