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Treatment of Landfill Leachate using Electrochemical Advanced Oxidation Processes (EAOPs)

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Abstract - One of the most complicated and dangerous waste waters produced during the breakdown of municipal solid waste (MSW) is landfill leachate. Refractory organic matter, ammonia, heavy metals, dissolved salts; xenobiotic compounds, pharmaceuticals, endocrine-disrupting chemicals, and other developing contaminants are present in high amounts. The composition of these contaminants varies depending on the age of the landfill, the climate, and the characteristics of the waste. Because of its low biodegradability, high toxicity, and complex chemical composition, mature landfill leachate frequently shows limited efficacy when treated using conventional treatment technologies, such as biological treatment, coagulation–flocculation, adsorption, membrane filtration, and chemical oxidation. As a result, there is a growing need for cutting-edge treatment methods that can effectively break down and fully mineralize persistent contaminants while reducing secondary pollution.

Electrochemical Advanced Oxidation Processes (EAOPs) have emerged as one of the most promising and environmentally sustainable technologies for the treatment of landfill leachate because of their ability to generate highly reactive oxygen species (ROS), particularly hydroxyl radicals (OH-), directly within the electrochemical reactor. Owing to their exceptionally high oxidation potential, these reactive species effectively and non-selectively degrade a broad spectrum of refractory organic contaminants into simpler intermediates, which are subsequently mineralized into carbon dioxide (CO_2), water (H_2O), and inorganic ions. Compared with conventional oxidation technologies, EAOPs offer several significant advantages, including *in situ* generation of oxidants, reduced chemical consumption, minimal sludge production, high oxidation efficiency, operational flexibility, and compatibility with integrated or hybrid treatment systems.

This review comprehensively examines the fundamental principles, reaction mechanisms, operational parameters, and recent technological developments of EAOPs for landfill leachate treatment. The major electrochemical technologies, including anodic oxidation (AO), Electro-Fenton (EF), Photoelectro-Fenton (PEF), Electro-Peroxone (EP), and emerging hybrid electrochemical oxidation processes, are systematically classified and critically evaluated with respect to their operating principles, reactor configurations, oxidation pathways, and pollutant degradation mechanisms. Particular emphasis is placed on the electrochemical generation of hydroxyl radicals, direct and indirect oxidation pathways, mineralization mechanisms, and kinetic models governing the degradation of persistent organic pollutants.

The review further discusses the influence of key operational parameters—including electrode materials, current density, solution pH, supporting electrolytes, reaction time, temperature, reactor configuration, and energy consumption—on the overall treatment efficiency of EAOPs. Recent advances in electrode engineering, especially the development of boron-doped diamond (BDD) electrodes, mixed metal oxide (MMO) anodes, carbon-based cathodes, nano structured electrode materials, and three-dimensional electrochemical reactors, are highlighted for their roles in improving oxidation efficiency, enhancing current utilization, increasing electrode durability, and reducing energy consumption.

In addition, the performance of EAOPs is critically assessed based on their ability to remove chemical oxygen demand (COD), mineralize total organic carbon (TOC), oxidize ammonia, eliminate color, remove heavy metals, reduce toxicity, and degrade emerging contaminants. Comparative analyses indicate that Electro-Fenton and Photoelectro-Fenton processes generally achieve superior mineralization efficiencies due to the continuous *in situ* generation of hydroxyl radicals, whereas anodic oxidation employing boron-doped diamond electrodes demonstrates exceptional oxidation capability for the degradation of highly refractory organic compounds. Furthermore, hybrid electrochemical systems integrating biological treatment, electro coagulation, membrane separation, photo catalysis, and per sulfate activation have shown considerable potential for enhancing treatment efficiency while reducing electrical energy consumption and overall operating costs.

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Despite significant advances in electrochemical wastewater treatment technologies, several challenges continue to limit the large-scale implementation of EAOPs. These include high electrical energy requirements, the elevated cost of advanced electrode materials, catalyst deactivation, electrode passivation, the formation of oxidation by-products, and challenges associated with process scale-up. This review discusses these limitations and examines recent industrial developments, including intelligent reactor design, renewable energy integration, artificial intelligence-assisted process optimization, digital monitoring systems, and resource recovery approaches within the framework of sustainable wastewater management and circular economy principles.

Finally, future research directions are identified, emphasizing the development of durable and cost-effective electrode materials, optimization of hybrid treatment technologies, comprehensive techno-economic and life-cycle assessments, long-term pilot- and full-scale validation studies, and the integration of renewable energy sources with advanced process control strategies. Overall, this review demonstrates that Electrochemical Advanced Oxidation Processes represent a highly efficient and environmentally sustainable platform for landfill leachate treatment and are expected to play a pivotal role in the next generation of wastewater treatment technologies, contributing to improved environmental protection, resource recovery, and sustainable waste management.

Keywords: Landfill leachate, electrochemical advanced oxidation processes (EAOPs), wastewater treatment, advanced oxidation processes, hydroxyl radicals, electro-Fenton process, anodic oxidation, chemical oxygen demand (COD) removal, total organic carbon (TOC) mineralization, emerging contaminants.

1. INTRODUCTION TO ELECTROCHEMICAL ADVANCED OXIDATION PROCESSES (EAOPs)

1.1 Definition, Importance, and Historical Context

Rapid industrialization, urbanization, and population growth have led to a significant increase in municipal solid waste (MSW) generation worldwide [1]. Among the various disposal methods, land filling remains one of the most widely used because of its relatively low operational cost, simple management, and ability to accommodate large quantities of waste [1], [2]. However, the infiltration of rainwater through landfill sites and the natural decomposition of waste produce a highly contaminated liquid known as landfill leachate [3]. This leachate contains a complex mixture of dissolved organic matter, ammonia, heavy metals, chlorinated compounds, pharmaceuticals, endocrine-disrupting chemicals, and other refractory pollutants [3], [4]. The characteristics of landfill leachate vary depending on landfill age, waste composition, climatic conditions, and operational practices, making its treatment a major environmental challenge [5].

Several conventional treatment technologies, including biological treatment, coagulation–flocculation, adsorption, membrane filtration, and chemical precipitation, have been applied for landfill leachate treatment [6]. Although these methods effectively remove biodegradable organic matter and suspended solids, they often show limited efficiency for mature landfill leachate containing persistent organic pollutants and low biodegradable fractions [6], [7]. In addition, problems such as excessive sludge generation, membrane fouling, high chemical consumption, and increased operating costs have encouraged researchers to investigate more efficient and environmentally sustainable treatment technologies [7], [8].

Advanced Oxidation Processes (AOPs) have emerged as promising alternatives because they generate highly reactive oxygen species (ROS), particularly hydroxyl radicals (•OH), which possess an oxidation potential of approximately 2.8 V [9]. These radicals react rapidly and non-selectively with refractory organic pollutants, converting them into simpler intermediate compounds and ultimately mineralizing them into carbon dioxide (CO_2), water (H_2O), and inorganic ions [9], [10]. Compared with conventional oxidation methods, AOPs provide faster reaction kinetics, higher degradation efficiencies, and lower secondary pollution [10], [11].

Among the different AOPs, Electrochemical Advanced Oxidation Processes (EAOPs) have attracted considerable attention over the past three decades [12]. EAOPs combine electrochemical reactions with advanced oxidation chemistry to generate oxidizing species directly within the treatment reactor [13]. Unlike conventional chemical oxidation processes that require continuous addition of chemical oxidants, EAOPs generate oxidants *in situ*, reducing chemical consumption, minimizing secondary waste generation, and providing better process control [13], [14]. The major EAOP technologies include anodic oxidation (AO), Electro-Fenton (EF), Photoelectro-Fenton (PEF), Electro-Peroxone (EP), electrochemical per sulfate activation, and electro coagulation-assisted oxidation [14], [15].

The development of EAOPs began with advances in electrochemical engineering and the introduction of dimensionally stable anodes and boron-doped diamond (BDD) electrodes [16]. Continuous improvements in electrode materials, reactor configurations, renewable energy integration, and hybrid treatment systems have significantly enhanced the efficiency and practical applicability

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of these technologies [17], [18]. Today, EAOPs are extensively investigated for treating landfill leachate, textile wastewater, pharmaceutical wastewater, petrochemical effluents, and various industrial wastewaters [18], [19].

Recent studies have reported chemical oxygen demand (COD) removal efficiencies exceeding 90%, significant color removal, efficient degradation of refractory organic compounds, and effective ammonia oxidation under optimized operating conditions [20], [21]. The treatment performance of EAOPs depends on several operational parameters, including electrode material, current density, solution pH, supporting electrolyte concentration, reaction time, hydraulic retention time, and reactor configuration [21], [22]. Ongoing research on nano structured electrodes, renewable energy utilization, and integrated electrochemical-biological treatment systems is expected to further improve energy efficiency and reduce operational costs [22], [23].

Overall, EAOPs have emerged as one of the most promising technologies for landfill leachate treatment because of their high oxidation efficiency, operational flexibility, environmental compatibility, and potential for complete mineralization of refractory pollutants [23], [24]. Current research focuses on improving reactor design, reducing energy consumption, extending electrode lifespan, and facilitating large-scale implementation to meet increasingly stringent environmental regulations [24], [25].

1.2 Characteristics and Composition of Landfill Leachate

Landfill leachate is a highly contaminated wastewater formed when rainwater, surface runoff, and the natural moisture present in municipal solid waste (MSW) pass through the landfill and dissolve different pollutants generated during waste decomposition [1], [7]. As the water moves through the waste layers, it carries both organic and inorganic contaminants, making landfill leachate one of the most difficult wastewaters to treat [7], [8]. The quantity and composition of leachate are not constant and depend on several factors, including landfill age, waste composition, rainfall, climatic conditions, and landfill management practices [7], [8].

The characteristics of landfill leachate change as the landfill becomes older. Young landfill leachate is produced during the early stage of waste degradation and contains a high concentration of biodegradable organic matter, volatile fatty acids, and ammonia [7], [8]. It usually has high biochemical oxygen demand (BOD) and chemical oxygen demand (COD) values, with a relatively high BOD/COD ratio, indicating that biological treatment can be effective [7], [13].

As the landfill reaches the methanogenic stage, the leachate becomes mature and its composition changes significantly [7]. Mature landfill leachate contains lower amounts of biodegradable organic matter but higher concentrations of refractory compounds such as humic substances, fulvic acids, phenolic compounds, and other persistent organic pollutants [7], [8]. Because of the low BOD/COD ratio, mature leachate is much more resistant to biological treatment and generally requires advanced treatment technologies such as Electrochemical Advanced Oxidation Processes (EAOPs) [4], [9].

Landfill leachate contains a wide range of contaminants. The major inorganic components include ammonium (NH_4^+), nitrate (NO_3^-), chloride (Cl^-), sulfate (SO_4^{2-}), bicarbonate (HCO_3^-), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), and potassium (K^+) **[1], [7]**. It also contains toxic heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), copper (Cu), zinc (Zn), mercury (Hg), and arsenic (As), which can accumulate in the environment and pose risks to human health and aquatic ecosystems [2], [7].

In recent years, researchers have also reported the presence of emerging contaminants in landfill leachate, including pharmaceuticals, personal care products, endocrine-disrupting compounds, pesticides, surfactants, micro plastics, and per- and poly fluro alkyl substances (PFAS) [4], [9], [12]. These contaminants are highly persistent and are often not completely removed by conventional treatment methods, creating additional environmental concerns.

Several physicochemical parameters are routinely used to evaluate landfill leachate quality. These include pH, electrical conductivity, total dissolved solids (TDS), total suspended solids (TSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), total organic carbon (TOC), ammonia nitrogen (NH_4^+–N), color, turbidity, and heavy metal concentrations [1], [7]. Among these parameters, COD and ammonia are considered the most important indicators because they are usually present at high concentrations and strongly influence treatment efficiency [7], [9].

Overall, the complex and highly variable nature of landfill leachate makes its treatment challenging. Since the composition changes with landfill age and environmental conditions, no single treatment method can effectively remove all pollutants. Therefore, integrated treatment approaches, particularly Electrochemical Advanced Oxidation Processes (EAOPs), have gained considerable attention because of their ability to degrade refractory organic compounds, reduce toxicity, and improve the overall quality of landfill leachate before discharge [4], [5], [9].

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1.3 Environmental Impacts of Landfill Leachate

Landfill leachate is considered one of the major environmental problems associated with municipal solid waste (MSW) disposal. If it is not properly collected and treated, leachate can seepage into the surrounding soil and contaminate groundwater, rivers, lakes, and nearby agricultural land [2], [3], [7]. Since groundwater is an important source of drinking water in many regions, leachate contamination can pose serious risks to human health and the environment [2], [7].

One of the main environmental concerns is the high concentration of organic pollutants present in landfill leachate. When untreated leachate is discharged into natural water bodies, it increases the biochemical oxygen demand (BOD) and chemical oxygen demand (COD) of the water [1], [7]. As a result, the dissolved oxygen level decreases, making it difficult for fish and other aquatic organisms to survive [7], [8]. In addition, landfill leachate contains high concentrations of ammonia, which is toxic to aquatic life and can promote eutrophication. Excess nutrients encourage excessive algal growth, reduce water quality, and disturb the natural balance of aquatic ecosystems [2], [7], [13].

Landfill leachate also contains refractory organic compounds such as humic substances, fulvic acids, phenolic compounds, and other persistent pollutants that are resistant to natural biodegradation [7], [8]. These pollutants remain in the environment for long periods and may continue to affect water quality even after conventional treatment. Therefore, advanced treatment technologies are often required to remove these contaminants effectively [4], [5], [9].

Another important concern is the presence of heavy metals, including lead (Pb), cadmium (Cd), chromium (Cr), mercury (Hg), nickel (Ni), copper (Cu), zinc (Zn), and arsenic (As) [2], [7]. These metals can accumulate in soil, sediments, plants, and aquatic organisms through bioaccumulation and bio magnification. Long-term exposure to heavy metals may cause kidney damage, nervous system disorders, developmental problems, and even cancer in humans [2], [7].

In recent years, the presence of emerging contaminants such as pharmaceuticals, personal care products, endocrine-disrupting chemicals, pesticides, and per- and poly fluoro alkyl substances (PFAS) has become another major environmental concern [4], [9], [12]. Even at very low concentrations, these contaminants may affect the hormonal systems of humans and wildlife and can have long-term ecological impacts because they are difficult to remove using conventional treatment methods [4], [12].

The effects of landfill leachate are not limited to water pollution. When leachate enters the soil, it can reduce soil fertility, alter soil microbial activity, and negatively affect agricultural productivity [7], [8]. In addition, the decomposition of organic waste in landfills produces greenhouse gases such as methane (CH_4) and carbon dioxide (CO_2), which contribute to global warming and climate change [3], [7].

Considering these environmental and public health risks, proper collection, monitoring, and treatment of landfill leachate are essential. Conventional treatment methods alone are often insufficient for removing refractory pollutants and emerging contaminants. Therefore, advanced treatment technologies, particularly Electrochemical Advanced Oxidation Processes (EAOPs), have gained significant attention because of their ability to degrade persistent organic pollutants, reduce toxicity, and improve the overall quality of landfill leachate before its discharge into the environment [4], [5], [9], [10].

1.4 Need for Advanced Treatment Technologies

Landfill leachate contains a wide variety of organic and inorganic pollutants, many of which are difficult to remove using conventional wastewater treatment methods [7], [8]. Over the years, several treatment technologies such as activated sludge, anaerobic digestion, coagulation–flocculation, adsorption, membrane filtration, and chemical precipitation have been widely used for landfill leachate treatment [7], [8], [14]. Although these methods are effective in removing suspended solids and biodegradable organic matter, they often fail to completely remove refractory organic compounds, ammonia, heavy metals, toxic micro pollutants, and emerging contaminants [7], [8], [12].

Conventional treatment processes also have several practical limitations. Biological treatment becomes less effective for mature landfill leachate because it contains a low proportion of biodegradable organic matter [7], [8]. Membrane-based systems may suffer from membrane fouling and require frequent cleaning or replacement, while coagulation and chemical precipitation produce large amounts of sludge that require additional treatment and disposal [8], [11]. Furthermore, the high consumption of chemicals and increasing operating costs reduce the economic feasibility of these treatment methods for long-term applications [8], [12].

In recent years, environmental regulations have become more stringent, requiring lower discharge limits for chemical oxygen demand (COD), total organic carbon (TOC), ammonia, heavy metals, and hazardous organic compounds before wastewater is

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released into the environment [2], [3]. As a result, researchers have focused on developing advanced treatment technologies that can completely degrade pollutants instead of simply transferring them from one phase to another [4], [12].

Among the available advanced treatment methods, Advanced Oxidation Processes (AOPs) **have** attracted significant attention because they generate highly reactive oxygen species (ROS), especially hydroxyl radicals (•OH), which are capable of oxidizing a wide range of organic pollutants with high efficiency [4], [12]. These radicals can break down complex and persistent organic compounds into smaller molecules and eventually convert them into carbon dioxide, water, and inorganic ions [4].

A major development in this field is the introduction of Electrochemical Advanced Oxidation Processes (EAOPs). These processes generate hydroxyl radicals and other reactive oxidizing species directly inside the electrochemical reactor through anodic oxidation, Electro-Fenton, Photoelectro-Fenton, Electro-Peroxone, and other electrochemical reactions [4], [5], [6], [9]. Since the oxidants are produced *in situ*, the requirement for external chemicals is reduced, secondary pollution is minimized, and the treatment process can be controlled more effectively [4], [5].

Many studies have shown that EAOPs can efficiently degrade refractory organic matter, reduce chemical oxygen demand (COD) and total organic carbon (TOC), remove color, decrease toxicity, and oxidize ammonia present in landfill leachate [5], [9], [10]. In addition, electrochemical treatment systems are compact, easy to automate, and can be combined with biological treatment, membrane filtration, photo catalysis, and other advanced treatment methods to improve overall performance [5], [6], [9]. Their compatibility with renewable electricity sources also makes them an environmentally sustainable option for future wastewater treatment systems [5].

Recent advances in electrode materials, nanotechnology, reactor design, and energy-efficient electrochemical systems have further improved the performance and reliability of EAOPs [5], [6], [10]. These developments have increased pollutant removal efficiency while reducing energy consumption and operating costs, making EAOPs more suitable for large-scale applications.

Overall, Electrochemical Advanced Oxidation Processes are increasingly recognized as one of the most effective and sustainable technologies for landfill leachate treatment [4], [5], [9]. Their ability to remove persistent pollutants, achieve high mineralization efficiency, produce less secondary waste, and integrate with other treatment technologies makes them a promising solution for meeting future environmental regulations and supporting sustainable wastewater management [4], [5], [10].

2. CLASSIFICATION OF ELECTROCHEMICAL ADVANCED OXIDATION PROCESSES (EAOPS)

Electrochemical Advanced Oxidation Processes (EAOPs) are a group of advanced wastewater treatment technologies that use electrochemical reactions to produce highly reactive oxidizing species for the degradation of pollutants [4], [5]. These processes mainly generate hydroxyl radicals (OH^-), sulfate radicals (SO_4^{--}), hydrogen peroxide (H_2O_2), ozone (O_3), and other reactive oxygen species (ROS), which have strong oxidation ability and can effectively degrade persistent organic contaminants present in landfill leachate and other industrial wastewaters [4]–[6], [12].

The main objective of EAOPs is to convert complex organic pollutants into simpler compounds and, whenever possible, completely mineralize them into carbon dioxide (CO_2), water (H_2O), and inorganic ions [4], [5]. Compared with conventional treatment methods, EAOPs require fewer chemical reagents, produce less secondary sludge, and provide higher removal efficiencies for refractory organic compounds and emerging contaminants [5], [6], [10].

EAOPs can be classified according to their oxidation mechanism, electrode material, reactor configuration, and the method used to generate oxidizing species [4], [5]. The major types of EAOPs include anodic oxidation (AO), Electro-Fenton (EF), Photoelectro-Fenton (PEF), Electro-Peroxone (EP), and emerging hybrid electrochemical oxidation technologies [4]–[6], [9]. Each process has its own operating principle, advantages, and limitations. The selection of a suitable EAOP depends on the characteristics of the wastewater, the type and concentration of pollutants, treatment objectives, and operating conditions [5], [9].

Among these technologies, anodic oxidation and Electro-Fenton are the most widely investigated for landfill leachate treatment because of their high oxidation efficiency and ability to remove refractory organic compounds [5], [9], [10]. In recent years, Photoelectro-Fenton, Electro-Peroxone, and hybrid EAOP systems have also gained significant attention due to their improved mineralization efficiency, lower energy consumption, and better performance in treating complex wastewaters [5], [6], [9]. Continuous advancements in electrode materials, reactor design, nanotechnology, and renewable energy integration are expected to further improve the efficiency and large-scale application of these technologies in sustainable landfill leachate treatment [5], [6], [10].

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2.1 Anodic Oxidation (AO)

Anodic oxidation (AO) is one of the simplest and most widely studied Electrochemical Advanced Oxidation Processes (EAOPs) for wastewater treatment [4]–[6]**.** In this process, pollutants are oxidized directly at the surface of the anode. During electrolysis, water molecules are oxidized to produce hydroxyl radicals (OH^-), which are highly reactive and can degrade a wide range of organic pollutants [4], [5]**.** These radicals attack complex organic compounds without much selectivity, breaking them into smaller intermediate molecules and eventually converting them into carbon dioxide (CO_2), water (H_2O), and inorganic ions [4], [10]**.**

The performance of anodic oxidation mainly depends on the type of electrode material used **[5], [6]**. Electrodes are generally classified as active and non-active anodes. Active anodes, such as platinum (Pt), ruthenium oxide (RuO_2), and iridium oxide (IrO_2), mainly promote selective oxidation through chemisorbed oxygen species [6], [10]**.** In contrast, non-active anodes, especially boron-doped diamond (BDD) electrodes, produce physisorbed hydroxyl radicals with much stronger oxidation power because of their high oxygen evolution over potential [5], [10]**.** As a result, BDD electrodes are more effective for degrading refractory organic pollutants and achieving a higher degree of mineralization [5], [10]**.**

The main anodic reaction is represented as:

$H_2O \rightarrow OH^- + H^+ + e^-$ [4], [5]

The generated hydroxyl radicals then react with organic pollutants according to the following reaction:

$R + OH^- \rightarrow CO_2 + H_2O$ + Mineralized Products [4]

Anodic oxidation has several advantages, including a simple reactor design, easy operation, high oxidation efficiency, and the ability to generate oxidizing species *in situ* without the addition of external chemical reagents [5], [6]**.** It also produces very little secondary sludge and can effectively remove persistent organic contaminants from landfill leachate and other industrial wastewaters [5], [10]**.**

Despite these advantages, anodic oxidation has some limitations. The process requires a relatively high electrical energy input, especially when treating highly concentrated wastewater [6], [10]**.** In addition, advanced electrode materials such as boron-doped diamond are expensive, which increases the overall treatment cost and limits large-scale industrial application [5], [10]**.** Therefore, current research is focused on developing low-cost electrode materials, improving reactor design, and reducing energy consumption to make anodic oxidation more economically feasible for large-scale landfill leachate treatment [5], [6].

2.2 Electro-Fenton Process (EF)

The Electro-Fenton (EF) process is one of the most effective Electrochemical Advanced Oxidation Processes (EAOPs) used for the treatment of landfill leachate and other industrial wastewaters [4], [5], [9]**.** This process is based on the continuous *in situ* generation of hydroxyl radicals (OH^-), which are highly reactive and capable of degrading a wide range of refractory organic pollutants [4], [9]**.** Unlike the conventional Fenton process, the Electro-Fenton method produces hydrogen peroxide electrochemically at the cathode and continuously regenerates ferrous ions (Fe^{2+}), reducing the need for external chemical addition and improving the overall treatment efficiency [4], [5]**.**

In the Electro-Fenton process, dissolved oxygen is reduced at the cathode to produce hydrogen peroxide (H_2O_2). The generated hydrogen peroxide then reacts with ferrous ions (Fe^{2+}) to produce hydroxyl radicals. During this reaction, ferric ions (Fe^{3+}) are formed and are continuously converted back to ferrous ions at the cathode, allowing the Fenton reaction to continue throughout the treatment process [4], [5], [9]**.**

The main electrochemical reactions involved in the Electro-Fenton process are as follows:

Cathode reaction:

$O_2 + 2H^+ + 2e^- \rightarrow H_2O_2$ [4]

Fenton reaction:

$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + OH^- + OH^-$ [4]

Regeneration of ferrous ions:

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$Fe^{3+} + e^{-} \rightarrow Fe^{2+}$ [4], [9]

The continuous regeneration of Fe^{2+} is one of the major advantages of the Electro-Fenton process because it maintains hydroxyl radical production throughout the reaction and minimizes chemical consumption [4], [9]. The generated hydroxyl radicals rapidly oxidize complex organic compounds, leading to significant reductions in chemical oxygen demand (COD), color, toxicity, and other persistent pollutants present in landfill leachate [5], [9], [10].

The performance of the Electro-Fenton process depends on several operating conditions. Among these, solution pH is one of the most important parameters. The optimum pH is generally between 2.5 and 3.5, where hydroxyl radical production is highest and the Fenton reaction proceeds efficiently [4], [9]. Other important factors include current density, iron concentration, dissolved oxygen availability, supporting electrolyte concentration, reaction time, and electrode material [5], [6], [9].

Many studies have reported excellent treatment performance using the Electro-Fenton process. Under optimized operating conditions, COD removal efficiencies of more than 90% have been achieved for landfill leachate [9], [13]. The process is especially effective for treating mature landfill leachate, which contains high concentrations of humic substances and refractory organic compounds that are difficult to remove by conventional biological treatment [7], [8], [9]. Because of its high oxidation efficiency, low sludge production, and ability to mineralize persistent pollutants, the Electro-Fenton process has become one of the most widely studied EAOPs for landfill leachate treatment [4], [5], [9].

2.3 Photoelectro-Fenton (PEF)

Photoelectro-Fenton (PEF) is an improved version of the Electro-Fenton (EF) process in which ultraviolet (UV) or visible light is combined with electrochemical oxidation to enhance pollutant degradation [4], [5], [9]. The addition of light increases the production of hydroxyl radicals (OH^{-}) by converting ferric ions (Fe^{3+}) back into ferrous ions (Fe^{2+}), allowing the Fenton reaction to continue more efficiently [4], [9]. This continuous regeneration of Fe^{2+} increases the oxidation capacity of the process and improves the degradation of refractory organic pollutants.

The main photochemical reaction involved in the PEF process is:

$Fe^{3+} + h\nu \rightarrow Fe^{2+}$ [4], [9]

The regenerated ferrous ions immediately react with hydrogen peroxide to produce additional hydroxyl radicals, resulting in faster degradation and greater mineralization of organic contaminants [4], [5]. Because of this additional photochemical reaction, the Photoelectro-Fenton process generally performs better than the conventional Electro-Fenton process [5], [9].

Several studies have shown that the PEF process achieves higher mineralization efficiency, faster reaction rates, and better removal of aromatic compounds, chlorinated pollutants, and other persistent organic contaminants [5], [9], [10]. It also reduces the concentration of residual iron in the treated effluent by promoting the continuous regeneration of Fe^{2+} [4], [9]. Under optimized operating conditions, Photoelectro-Fenton has been reported to achieve COD removal efficiencies greater than 95% during landfill leachate treatment [9].

The performance of the PEF process depends on several operating parameters, including solution pH, current density, iron concentration, hydrogen peroxide production, light intensity, reaction time, and electrode material [4], [5], [9]. Similar to the Electro-Fenton process, the optimum pH is generally maintained between 2.5 and 3.5 to maximize hydroxyl radical generation and pollutant degradation [4], [9].

Although the Photoelectro-Fenton process provides excellent treatment performance, it also has some limitations. The requirement for an external UV or visible light source increases both the initial investment and energy consumption of the treatment system [5], [9]. To overcome this limitation, recent studies have focused on using solar radiation as an alternative light source to reduce operating costs and improve the economic feasibility of the process [4], [5], [9].

Overall, Photoelectro-Fenton is considered one of the most effective EAOPs for landfill leachate treatment because it combines electrochemical oxidation with photochemical reactions to generate a larger amount of hydroxyl radicals. This results in higher pollutant removal efficiency, improved mineralization, and better treatment of refractory organic compounds compared with the conventional Electro-Fenton process [4], [5], [9], [10].

2.4 Electro-Peroxone Process (EP)

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The Electro-Peroxone (EP) process is an advanced Electrochemical Advanced Oxidation Process (EAOP) that combines electrochemical hydrogen peroxide (H_2O_2) generation with ozone (O_3) oxidation to improve the production of hydroxyl radicals (OH^-) [4], [5], [12]. In this process, hydrogen peroxide is generated electrochemically inside the reactor, while ozone is supplied from an external source. The reaction between ozone and hydrogen peroxide produces a large number of hydroxyl radicals, which are highly effective in degrading refractory organic pollutants [4], [5].

The main reaction involved in the Electro-Peroxone process is:

$O_3 + H_2O_2 \rightarrow OH^- + O_2 + HO_2$ [4], [12]

The combination of electrochemical oxidation and ozonation creates a strong synergistic effect, resulting in faster degradation and higher mineralization of organic contaminants than either process used alone [4], [5], [6]. The large amount of hydroxyl radicals produced during the reaction helps remove persistent pollutants that are difficult to degrade by conventional treatment methods [5], [12].

Several studies have shown that the Electro-Peroxone process is effective in removing color, phenolic compounds, pharmaceuticals, endocrine-disrupting chemicals, humic substances, and other refractory pollutants commonly present in mature landfill leachate [5], [9], [10], [12]. The process also provides significant reductions in chemical oxygen demand (COD) and improves the overall quality of treated wastewater [5], [9]. Under optimized operating conditions, COD removal efficiencies of more than 90% have been reported with shorter treatment times than those required for conventional electrochemical oxidation processes [5], [12].

Compared with conventional ozonation, the Electro-Peroxone process offers higher oxidation efficiency because the continuous generation of hydrogen peroxide increases hydroxyl radical production while reducing ozone consumption [4], [5]. This improves pollutant degradation and makes the process more effective for treating complex wastewaters such as landfill leachate [5], [9].

The treatment performance of the Electro-Peroxone process depends on several operating parameters, including ozone dosage, current density, hydrogen peroxide generation rate, solution pH, reaction time, and reactor configuration [4], [5], [12]. Proper optimization of these parameters is essential for achieving high pollutant removal efficiency while minimizing energy consumption.

Although the Electro-Peroxone process has excellent oxidation capability, it also has some limitations. The need for an ozone generator increases the installation cost, energy consumption, and operational complexity of the treatment system [5], [6]. Despite these challenges, ongoing research is focused on improving reactor design, increasing energy efficiency, and integrating the Electro-Peroxone process with other advanced treatment technologies to reduce operating costs and enhance large-scale application [5], [9], [12].

2.5 Emerging Hybrid EAOP Technologies

In recent years, significant progress in electrochemical engineering has led to the development of hybrid Electrochemical Advanced Oxidation Processes (EAOPs). These systems combine electrochemical oxidation with physical, chemical, or biological treatment methods to improve pollutant removal efficiency while reducing energy consumption and operating costs [4], [5], [6]. Hybrid technologies are becoming increasingly popular because a single treatment method is often not sufficient to treat the complex composition of landfill leachate [5], [7].

Several hybrid EAOP technologies have been developed for wastewater treatment. Some of the most commonly studied systems include electrochemical oxidation combined with biological treatment, electro coagulation–electro oxidation, photo electro chemical oxidation using semiconductor photo catalysts such as TiO_2, sono electro chemical oxidation assisted by ultrasonic cavitation, electrochemical activation of per sulfate or per oxy mono sulfate for sulfate radical generation, membrane–electrochemical hybrid reactors, and solar-powered Electro-Fenton and Photoelectro-Fenton systems [4]–[6], [9], [10]. These integrated technologies take advantage of the strengths of different treatment processes to achieve better overall performance.

Hybrid EAOP systems offer several important benefits compared with individual treatment methods. They can improve the degradation of refractory organic compounds and emerging contaminants, increase mineralization efficiency, reduce sludge production, and lower overall energy consumption [5], [9], [10]. Many hybrid systems also shorten treatment time and improve the quality of the treated effluent, making them suitable for treating mature landfill leachate and other complex industrial wastewaters [5], [7], [9].

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Recent developments in electrode materials have further improved the performance of hybrid EAOPs. The use of nano structured electrodes, carbon-based catalysts, conductive polymers, and advanced catalytic materials has increased oxidation efficiency and enhanced the production of reactive oxygen species [5], [6], [10]. In addition, the integration of renewable energy sources such as solar power has helped reduce electricity consumption and improve the environmental sustainability of these treatment systems [5], [9].

Current research is mainly focused on developing more efficient and cost-effective hybrid technologies for large-scale applications [5], [6]. Researchers are working on advanced reactor designs, real-time process monitoring, artificial intelligence (AI)-based process optimization, and smart control systems to improve treatment performance and reduce operating costs [5], [9]. The combination of renewable energy with intelligent process control is also expected to increase the commercial feasibility of hybrid EAOPs in the future.

Overall, emerging hybrid EAOP technologies provide a promising approach for landfill leachate treatment because they combine the advantages of different treatment methods in a single system [4], [5], [9]. Their high pollutant removal efficiency, lower sludge production, improved energy utilization, and flexibility make them attractive for future sustainable wastewater treatment and large-scale industrial applications [5], [6], [10].

3. REACTION MECHANISMS OF ELECTROCHEMICAL ADVANCED OXIDATION PROCESSES (EAOPS)

Electrochemical Advanced Oxidation Processes (EAOPs) remove pollutants mainly through the generation of highly reactive oxygen species (ROS), especially hydroxyl radicals (OH^-), which have a high oxidation potential of about 2.80 V [4], [12]. These radicals are strong oxidizing agents and can react rapidly with a wide range of organic pollutants without being highly selective. As a result, complex organic compounds are broken down into smaller intermediate products and are eventually converted into carbon dioxide (CO_2), water (H_2O), and inorganic ions through the mineralization process [4], [5].

The effectiveness of EAOPs depends on several factors, including the amount of reactive species generated, the nature and concentration of pollutants, operating conditions such as pH and current density, the type of electrode material, and the design of the electrochemical reactor [5], [6], [9]. A higher production of reactive oxygen species generally improves pollutant degradation and increases the overall treatment efficiency [4], [5].

Different EAOPs produce reactive oxidizing species through different electrochemical pathways. However, the main degradation mechanism is based on the formation of hydroxyl radicals, which attack organic pollutants and initiate a series of oxidation reactions that ultimately lead to their complete or partial mineralization [4], [5], [10]. In some advanced systems, additional oxidizing species such as sulfate radicals (SO_4^{-}), hydrogen peroxide (H_2O_2), ozone (O_3), and superoxide radicals (O_2^{-}) also participate in the degradation process, further improving treatment performance [5], [12].

The major reaction mechanisms involved in EAOPs, including hydroxyl radical generation, direct and indirect oxidation pathways, mineralization mechanisms, and the factors affecting reaction kinetics, are discussed in the following sections [4], [5], [6].

3.1 Hydroxyl Radical Generation

Hydroxyl radicals (OH-) are the main reactive species responsible for the degradation of pollutants in most Electrochemical Advanced Oxidation Processes (EAOPs). These highly reactive radicals are generated either directly on the surface of the electrodes or indirectly through electrochemical reactions that take place in the solution. Once formed, hydroxyl radicals rapidly react with organic contaminants, breaking them into smaller compounds and finally converting them into carbon dioxide (CO_2), water (H_2O), and inorganic ions [4], [5], [12].

3.1.1 Direct Electrochemical Generation

In anodic oxidation, hydroxyl radicals (OH^-) are produced directly on the surface of the anode through the electrochemical oxidation of water molecules [4], [5]. These hydroxyl radicals are highly reactive and remain temporarily attached to the electrode surface, where they immediately react with nearby organic pollutants. This reaction breaks down complex organic compounds into simpler molecules, which are eventually converted into carbon dioxide (CO_2), water (H_2O), and inorganic ions [4], [5], [10].

The main reaction involved in this process is:

$H_2O \rightarrow OH^- + H^+ + e^-$ [4], [5]

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The efficiency of direct electrochemical oxidation mainly depends on the type of electrode material used [5], [6]. Non-active electrodes, especially boron-doped diamond (BDD) electrodes, produce weakly adsorbed hydroxyl radicals with very high oxidation power, making them highly effective for the degradation and mineralization of refractory organic pollutants [5], [10]. In contrast, active electrodes such as platinum (Pt), ruthenium oxide (RuO_2), and iridium oxide (IrO_2) generate more strongly adsorbed oxygen species, which generally promote selective oxidation instead of complete mineralization [6], [10]. Therefore, selecting a suitable electrode material is an important factor in improving the efficiency of the anodic oxidation process [5], [6].

3.1.2 Indirect Electrochemical Generation

In Electro-Fenton (EF) and other related EAOPs, hydroxyl radicals (OH^-) are generated indirectly through a series of electrochemical and chemical reactions [4], [5], [9]. In this process, hydrogen peroxide (H_2O_2) is first produced electrochemically at the cathode by reducing dissolved oxygen. The generated hydrogen peroxide then reacts with ferrous ions (Fe^{2+}) through the Fenton reaction to produce highly reactive hydroxyl radicals, which are responsible for the degradation of organic pollutants [4], [9].

The main reactions involved in the Electro-Fenton process are given below:

Cathode reaction:

$O_2 + 2H^+ + 2e^- \rightarrow H_2O_2$ [4]

Fenton reaction:

$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + OH^- + OH^-$ [4], [9]

Catalyst regeneration:

$Fe^{3+} + e^- \rightarrow Fe^{2+}$ [4], [9]

One of the main advantages of the Electro-Fenton process is the continuous regeneration of Fe^{2+} at the cathode. This allows the Fenton reaction to continue throughout the treatment process, ensuring a constant production of hydroxyl radicals and improving the degradation of refractory organic compounds present in landfill leachate [4], [5], [9].

Besides hydroxyl radicals, some EAOPs also produce other reactive oxygen species (ROS), such as superoxide radicals ($O_2^{\cdot-}$), hydro peroxyl radicals (HO_2^-), singlet oxygen ($^1O_2$), ozone (O_3), and sulfate radicals ($SO_4^{\cdot-}$) [5], [10], [12]. Although hydroxyl radicals are the primary oxidizing species in most electrochemical oxidation processes, these additional oxidants also contribute to pollutant degradation depending on the electrode material, electrolyte composition, and oxidation pathway used [5], [6], [12]. The combined action of these reactive species improves the overall oxidation efficiency and helps achieve higher pollutant removal during landfill leachate treatment [5], [9].

3.2 Direct and Indirect Oxidation Pathways

In Electrochemical Advanced Oxidation Processes (EAOPs), organic pollutants are removed through two main mechanisms: direct oxidation and indirect oxidation [4], [5], [6]. In direct oxidation, pollutants are oxidized by transferring electrons directly to the anode surface. This process mainly depends on the electrode material and the contact between the pollutant and the electrode [5], [6]. On the other hand, indirect oxidation occurs through reactive oxygen species (ROS), especially hydroxyl radicals (•OH), which are generated during electrochemical reactions. These highly reactive species attack and degrade organic contaminants in the solution, leading to their breakdown into smaller compounds and finally into carbon dioxide (CO_2), water (H_2O), and inorganic ions [4], [5], [10].

Both oxidation pathways play an important role in improving the treatment efficiency of EAOPs. The contribution of each pathway depends on factors such as the type of electrode, operating conditions, and the nature of the pollutants present in the wastewater [5], [6], [9].

3.2.1 Direct Oxidation

In the direct oxidation process, organic pollutants are first adsorbed onto the surface of the anode, where they lose electrons through a direct electron-transfer reaction [5], [6]. In this mechanism, the oxidation of pollutants takes place without the direct involvement of free radicals. As the reaction continues, the contaminants are converted into partially oxidized intermediate

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compounds or completely mineralized into carbon dioxide (CO_2), water (H_2O), and inorganic ions, depending on the operating conditions and the electrode material used [4], [5], [10].

The general reaction for direct oxidation can be written as:

$R \rightarrow$ Oxidized Products + ne^- [4], [6]

Where R represents the organic pollutant and n is the number of electrons transferred during the oxidation reaction.

The efficiency of direct oxidation mainly depends on the adsorption of pollutants on the electrode surface and the electro catalytic activity of the anode [5], [6]. Pollutants that are easily adsorbed onto the electrode are generally oxidized more effectively. In addition, electrode materials with high electro catalytic activity improve the oxidation rate and increase the overall treatment efficiency [5], [10]. Therefore, the selection of a suitable electrode material is an important factor in achieving effective pollutant degradation in EAOPs [5], [6].

3.2.2 Indirect Oxidation

Indirect oxidation is the main pollutant degradation mechanism in most Electrochemical Advanced Oxidation Processes (EAOPs) [4], [5]. In this process, highly reactive oxidizing species, especially hydroxyl radicals (OH^-), are generated through electrochemical reactions and move freely throughout the solution. These reactive species can attack and degrade organic pollutants without requiring direct contact between the pollutants and the electrode surface [4], [5], [9].

The general oxidation reaction can be written as:

$R + OH^- \rightarrow$ Oxidized Intermediates [4], [5]

Where R represents the organic pollutant.

Hydroxyl radicals degrade organic compounds through several reaction mechanisms, including hydrogen atom abstraction, electrophilic addition to double bonds, electron transfer, aromatic ring hydroxylation, and cleavage of carbon–carbon (C–C) and carbon–heteroatom (C–X) bonds [4], [10], [12]. These reactions gradually break large and complex organic molecules into smaller oxygen-containing intermediate compounds. With continued oxidation, these intermediates are further degraded and finally converted into carbon dioxide (CO_2), water (H_2O), and inorganic ions [4], [5], [10].

The combined action of direct and indirect oxidation significantly improves the overall performance of EAOPs [5], [6]. While direct oxidation occurs on the electrode surface, indirect oxidation takes place throughout the solution, allowing the treatment process to remove a wide range of refractory organic pollutants more efficiently [5], [9], [10]. This combined mechanism is one of the main reasons why EAOPs are highly effective for treating complex wastewaters such as landfill leachate [5], [7].

3.3 Mineralization Mechanisms

One of the main advantages of Electrochemical Advanced Oxidation Processes (EAOPs) is their ability to completely degrade organic pollutants instead of simply transferring them from one phase to another, as often happens in conventional treatment methods [4], [5]. The main objective of EAOPs is to achieve mineralization, where complex organic compounds are converted into stable inorganic products such as carbon dioxide (CO_2), water (H_2O), nitrate (NO_3^-), sulfate (SO_4^{2-}), phosphate (PO_4^{3-}), and chloride (Cl^-) ions [4], [12].

The mineralization of pollutants generally occurs in three stages.

Stage I: Initial Oxidation

In the first stage, hydroxyl radicals (OH^-) attack the parent organic pollutants and begin to break them into smaller intermediate compounds. These products mainly include hydro oxalates compounds, aldehydes, ketones, alcohols, and short-chain organic acids [4], [5].

Stage II: Intermediate Degradation

The intermediate compounds formed during the first stage continue to react with hydroxyl radicals. As oxidation proceeds, aromatic rings are broken, aliphatic chains are degraded, and low-molecular-weight organic acids such as oxalic acid, formic acid, and acetic acid are produced [5], [10].

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Stage III: Complete Mineralization

In the final stage, the remaining intermediate compounds are further oxidized into stable inorganic products. The overall mineralization reaction can be represented as:

Organic Compounds + $OH^- \rightarrow CO_2 + H_2O$ + Inorganic Ions [4], [5]

The efficiency of the mineralization process is commonly evaluated using Total Organic Carbon (TOC) removal, Chemical Oxygen Demand (COD) reduction, and Biochemical Oxygen Demand (BOD) measurements [1], [4]**.** Among these parameters, TOC removal is considered one of the best indicators of complete mineralization because it measures the actual reduction of organic carbon rather than the formation of intermediate products [4], [5]**.**

Achieving a high degree of mineralization is important because it reduces the formation of toxic intermediate compounds and lowers the environmental impact of the treated wastewater [5], [10], [12]**.** For this reason, EAOPs are considered an effective and environmentally friendly technology for the treatment of landfill leachate containing refractory organic pollutants [5], [7]**.**

3.4 Factors Influencing Reaction Kinetics

The reaction rate of Electrochemical Advanced Oxidation Processes (EAOPs) depends on several operating and physicochemical factors. These factors affect the generation of hydroxyl radicals (OH^-), pollutant degradation, and the overall treatment efficiency [4], [5], [6]**.** Among them, the type of electrode material, current density, and solution pH are considered the most important.

3.4.1 Electrode Material

The choice of electrode material has a major influence on the performance of EAOPs **[5], [6]**. Different electrodes produce different amounts of reactive oxygen species, which directly affect the oxidation efficiency. Boron-doped diamond (BDD) electrodes are considered one of the best electrode materials because of their high oxygen evolution potential and their ability to generate a large number of free hydroxyl radicals, resulting in efficient degradation and mineralization of refractory organic pollutants [5], [10]**.** Other commonly used electrode materials include graphite, platinum (Pt), titanium-based mixed metal oxide (MMO) electrodes, and carbon felt, which are selected based on the type of EAOP and wastewater characteristics [5], [6], [10]**.**

3.4.2 Current Density

Current density is another important operating parameter because it controls the rate of electrochemical reactions occurring at the electrode surface [4], [5]**.** Increasing the current density generally increases the production of hydroxyl radicals, leading to faster degradation of organic pollutants and higher treatment efficiency [5], [9]**.** However, if the current density becomes too high, unwanted side reactions such as oxygen evolution may occur. These side reactions reduce current efficiency and increase electrical energy consumption, making the treatment process less economical [5], [6]**.** Therefore, selecting an optimum current density is necessary to achieve efficient pollutant removal with lower energy consumption [4], [5]**.**

3.4.3 Solution pH

The pH of the solution plays an important role in controlling hydroxyl radical generation, catalyst stability, and pollutant degradation [4], [9]**.** In the Electro-Fenton process, the best performance is usually obtained under acidic conditions, with an optimum pH between 2.5 and 3.5, where hydroxyl radical production is maximum and iron catalysts remain stable [4], [9]**.** In contrast, anodic oxidation can operate effectively over a wider pH range depending on the electrode material [5], [6]**.** Very high or very low pH values may decrease treatment efficiency by reducing catalyst activity or promoting radical scavenging reactions, which consume hydroxyl radicals before they react with pollutants [4], [12]**.**

3.4.4 Electrode Spacing and Reactor Design

The distance between the anode and cathode plays an important role in the performance of EAOPs [5], [6]**.** Proper electrode spacing reduces electrical resistance, improves current distribution, and enhances mass transfer inside the reactor. In addition, a well-designed electrochemical reactor allows pollutants to reach the reactive sites more easily, resulting in better oxidation efficiency while reducing energy losses [5], [9]**.**

3.4.5 Electrolyte Concentration

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Supporting electrolytes are added to increase the electrical conductivity of the solution and improve the efficiency of electrochemical reactions [5], [6]. Sodium sulfate (Na_2SO_4) is one of the most commonly used supporting electrolytes because it increases conductivity without producing harmful by-products [5]. In contrast, chloride-containing electrolytes can generate active chlorine species during electrolysis. These species can enhance pollutant degradation but may also lead to the formation of chlorinated by-products, which can be harmful to the environment [6], [10].

3.4.6 Initial Pollutant Concentration

The initial concentration of pollutants also affects the degradation rate of EAOPs [4], [5]. Wastewater containing higher concentrations of organic pollutants generally requires longer treatment times and greater production of oxidizing species to achieve complete degradation [5], [9]. In many cases, the degradation of organic contaminants follows pseudo-first-order reaction kinetics, where the reaction rate depends on both the pollutant concentration and the availability of hydroxyl radicals [4], [12].

3.4.7 Temperature and Reaction Time

Temperature and reaction time are important operating parameters that influence the efficiency of electrochemical oxidation [5], [6]. Increasing the temperature usually speeds up electrochemical reactions and improves mass transfer, which can enhance pollutant degradation [5]. However, very high temperatures may accelerate the decomposition of hydrogen peroxide and increase energy consumption, reducing the overall process efficiency [4], [9]. Similarly, an adequate reaction time is necessary to achieve complete mineralization, especially when treating mature landfill leachate containing refractory organic compounds [5], [7].

3.4.8 Dissolved Oxygen Availability

Dissolved oxygen is an important factor in Electro-Fenton and Electro-Peroxone processes because it acts as the main source for hydrogen peroxide production at the cathode [4], [9]. A higher dissolved oxygen concentration improves hydrogen peroxide generation, leading to greater hydroxyl radical production and better pollutant degradation [4], [5]. Therefore, maintaining sufficient oxygen transfer during treatment helps improve the overall oxidation efficiency of these electrochemical processes [5], [9].

Overall, the reaction kinetics of EAOPs are influenced by several factors, including electrode material, current density, solution pH, electrode spacing, reactor design, electrolyte concentration, pollutant concentration, temperature, reaction time, and dissolved oxygen availability [4]–[6], [9]. Careful optimization of these parameters is essential to maximize pollutant degradation, improve energy efficiency, reduce operating costs, and achieve effective treatment of landfill leachate [5], [7], [10].

4. OPERATIONAL PARAMETERS AFFECTING EAOP PERFORMANCE

The performance of Electrochemical Advanced Oxidation Processes (EAOPs) is influenced by several operating parameters that control the generation of reactive oxygen species (ROS), pollutant degradation, mineralization efficiency, and energy consumption [4], [5]. Proper optimization of these parameters is important to achieve high treatment efficiency while reducing operating costs. The main factors include electrode materials, current density, solution pH, supporting electrolytes, reaction time, temperature, reactor design, and energy consumption [4]–[6].

4.1 Electrode Materials

The type of electrode material is one of the most important factors affecting the performance of EAOPs because it influences the generation of oxidizing species, electro catalytic activity, oxygen evolution potential, chemical stability, and electrode life [5], [6]. Based on their oxidation behavior, anode materials are generally divided into active anodes **and** non-active anodes.

Active anodes, such as platinum (Pt), iridium oxide (IrO_2), ruthenium oxide (RuO_2), and mixed metal oxide (MMO) electrodes, mainly produce chemisorbed oxygen species that selectively oxidize organic pollutants [5], [6]. These electrodes usually have a lower oxygen evolution potential and are more suitable for partial oxidation than complete mineralization [6], [10].

Non-active anodes, including boron-doped diamond (BDD), tin oxide (SnO_2), and lead dioxide (PbO_2), generate weakly adsorbed hydroxyl radicals with a much higher oxidation ability [5], [10]. Among these materials, BDD electrodes are widely considered the most effective because they have a high oxygen evolution over potential, excellent chemical stability, good corrosion resistance, a wide electrochemical window, and the ability to achieve near-complete mineralization of refractory organic pollutants [5], [10].

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Cathode materials also play an important role, especially in the Electro-Fenton process, where hydrogen peroxide is produced through the electrochemical reduction of oxygen [4], [9]. Common cathode materials include carbon felt, graphite felt, carbon cloth, activated carbon fiber, carbon nano tubes, and gas diffusion electrodes. These materials are preferred because they provide a large surface area, high electrical conductivity, and good catalytic activity for hydrogen peroxide generation [5], [9].

In recent years, researchers have focused on developing advanced electrode materials such as graphene-based composites, nano structured electrodes, doped carbon materials, titanium-based nano materials, and conductive polymers [5], [10]. These new materials help improve catalytic activity, increase hydroxyl radical production, reduce energy consumption, and extend the service life of electrodes. As a result, they have the potential to improve the overall efficiency and sustainability of EAOPs for landfill leachate treatment [5], [9], [10].

4.2 Current Density

Current density is one of the most important operating parameters in Electrochemical Advanced Oxidation Processes (EAOPs) because it controls the rate of electrochemical reactions at the electrode surface [4], [5]. It directly affects the generation of hydroxyl radicals (OH^-), hydrogen peroxide (H_2O_2), and other reactive oxygen species responsible for pollutant degradation [4], [9].

At low current densities, the production of oxidizing species is limited, resulting in slower degradation of pollutants and lower mineralization efficiency [5], [6]. As the current density increases, more hydroxyl radicals are produced, which improves the removal of Chemical Oxygen Demand (COD), Total Organic Carbon (TOC), color, and other refractory organic compounds [5], [9].

However, using very high current densities is not always beneficial. Excessive current can promote unwanted side reactions such as oxygen evolution at the anode and hydrogen evolution at the cathode. These reactions reduce current efficiency, increase electrical energy consumption, and may shorten the lifetime of the electrodes [5], [6].

Therefore, selecting an optimum current density is important to achieve high pollutant removal while keeping energy consumption and operating costs as low as possible. The optimum value depends on the type of electrode, wastewater characteristics, reactor design, and treatment objectives [4], [5].

4.3 Solution pH

The pH of the solution has a significant effect on the performance of EAOPs because it influences hydroxyl radical generation, catalyst stability, pollutant speciation, and oxidation efficiency [4], [5]. Among different EAOPs, the Electro-Fenton process is the most sensitive to changes in pH [4], [9].

The best performance of the Electro-Fenton process is generally achieved at a pH between 2.5 and 3.5. Under these acidic conditions, ferrous ions (Fe^{2+}) remain dissolved in the solution and efficiently react with hydrogen peroxide to generate hydroxyl radicals [4], [9]. At higher pH values, ferric ions (Fe^{3+}) form iron hydroxide precipitates, reducing catalyst availability and lowering the oxidation efficiency [9]. On the other hand, extremely low pH values may reduce the stability of hydrogen peroxide and increase the corrosion of reactor components [4], [5].

Compared to the Electro-Fenton process, anodic oxidation can operate effectively over a wider pH range [5], [6]. However, when chloride-containing electrolytes are used, the pH can influence the formation of active chlorine species, which may affect pollutant degradation and lead to the formation of chlorinated by-products [6], [10].

Therefore, maintaining an appropriate pH is essential for improving oxidation efficiency, reducing chemical consumption, and ensuring stable long-term operation of EAOPs [4], [5].

4.4 Supporting Electrolytes

Supporting electrolytes are added to electrochemical systems to improve the electrical conductivity of the solution and reduce electrical resistance [5], [6]. Better conductivity helps maintain uniform current distribution inside the reactor, lowers the required cell voltage, and improves the overall energy efficiency of the treatment process [5].

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Common supporting electrolytes used in EAOPs include sodium sulfate (Na_2SO_4), sodium chloride (NaCl), potassium sulfate (K_2SO_4), sodium nitrate ($NaNO_3$), and sodium carbonate (Na_2CO_3) [5], [6]. Among these, sodium sulfate (Na_2SO_4) is the most widely used because it is chemically stable and does not produce harmful chlorinated by-products during electrolysis [5].

When chloride-containing electrolytes such as NaCl are used, active chlorine species including chlorine (Cl_2), hypochlorous acid (HOCl), and hypochlorite ions (OCl^-) are produced [6], [10]. These oxidizing species can improve the degradation of organic pollutants through indirect oxidation. However, high chloride concentrations may also lead to the formation of chlorinated organic compounds, chlorate, and perchlorate, which can have negative environmental impacts [6], [10].

For this reason, the concentration and type of supporting electrolyte should be carefully selected. An optimum electrolyte concentration improves conductivity and treatment efficiency while minimizing energy consumption, operating costs, and the formation of undesirable by-products [5], [6].

4.5 Reaction Time

Reaction time is an important operating parameter in EAOPs because it determines how long the pollutants remain in contact with the electrochemically generated oxidizing species [4], [5]. In general, increasing the reaction time improves pollutant degradation and mineralization, as the generated hydroxyl radicals continue to oxidize both the original pollutants and the intermediate compounds [4], [9].

At the beginning of the treatment process, the degradation rate is usually high because the concentration of pollutants is greater and more hydroxyl radicals are available for oxidation [5], [12]. As the reaction continues, the degradation rate gradually decreases because most of the easily degradable compounds have already been removed, leaving more stable intermediate products that require additional oxidation [5], [10].

If the reaction time is too short, complete degradation cannot be achieved. On the other hand, excessively long treatment times increase electricity consumption while providing only a small improvement in pollutant removal [5], [6]. Therefore, selecting an optimum reaction time is necessary to achieve efficient treatment at a reasonable operating cost. Reaction time is commonly optimized based on COD removal, TOC reduction, color removal, ammonia oxidation, and kinetic studies [1], [5], [9].

4.6 Temperature

Temperature also affects the performance of EAOPs by influencing reaction kinetics, solution conductivity, mass transfer, and the stability of oxidizing species [4], [5]. A moderate increase in temperature generally increases the reaction rate and improves the movement of pollutants toward the electrode surface, resulting in better oxidation efficiency [5], [6].

Higher temperatures reduce solution viscosity and improve ionic mobility, which enhances electrochemical reactions [5]. However, very high temperatures may accelerate the decomposition of hydrogen peroxide, decrease dissolved oxygen concentration, increase evaporation losses, and promote unwanted side reactions that reduce current efficiency [4], [9].

For these reasons, most EAOP systems are operated close to room temperature, usually between 20 and 35 °C, where good treatment performance can be achieved with lower energy consumption [5], [9]. Temperature optimization becomes more important in large-scale treatment plants where environmental conditions may vary throughout the year [6].

4.7 Reactor Configuration

The design of the electrochemical reactor has a significant effect on the overall performance of EAOPs because it influences current distribution, mass transfer, hydraulic conditions, and pollutant removal efficiency [5], [6]. Several reactor designs have been developed, including batch reactors, continuous-flow reactors, parallel-plate reactors, tubular reactors, fluidized-bed reactors, rotating disk reactors, membrane electrochemical reactors, and three-dimensional electrode reactors [5], [10].

Batch reactors are mainly used in laboratory-scale studies because they are simple to construct and operate **[5]**. In contrast, continuous-flow reactors are more suitable for industrial applications because they can continuously treat large volumes of wastewater under stable operating conditions [6], [7].

Among the different reactor designs, three-dimensional electrochemical reactors have received considerable attention because they contain conductive particle electrodes that provide a much larger active surface area than conventional two-dimensional systems

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[5], [10]. This increases hydroxyl radical production, improves pollutant adsorption, enhances current efficiency, and accelerates the degradation of contaminants [5], [10].

Important factors considered during reactor design include electrode spacing, electrode arrangement, hydraulic retention time, flow rate, mixing conditions, gas diffusion, and reactor scale-up [5], [6]. A properly designed reactor improves mass transfer, reduces electrical resistance, enhances oxidation efficiency, and lowers operating costs [5], [9].

4.8 Energy Consumption

Electrical energy consumption is one of the major challenges limiting the large-scale application of EAOPs [5], [6]. The amount of energy required depends on several factors, including current density, cell voltage, treatment time, electrode material, reactor configuration, wastewater conductivity, and pollutant concentration [4], [5].

Generally, increasing the current density or extending the reaction time improves pollutant degradation but also increases electricity consumption [5], [9]. Therefore, operating conditions should be carefully optimized to obtain high treatment efficiency while minimizing energy costs [4], [5].

Several approaches have been suggested to improve the energy efficiency of EAOPs. These include:

- Using high-performance electrode materials with low over potential [5], [10].
- Optimizing current density and electrode spacing [5], [6].
- Combining EAOPs with biological treatment or membrane processes [5], [7].
- Using renewable energy sources such as solar and wind power [9].
- Applying intelligent process control and real-time monitoring systems [5].
- Using three-dimensional electrode reactors to improve current utilization [5], [10].

The energy performance of EAOPs is commonly evaluated using Electrical Energy per Order (EEO), specific energy consumption (kWh m^{-3}), and energy consumption per kilogram of COD removed [5], [6]. These parameters are useful for comparing different electrochemical technologies and evaluating their economic feasibility for full-scale applications [5], [9].

Overall, the efficiency of EAOPs depends on the combined effects of operating conditions, wastewater characteristics, and reactor design [4]–[6]. Proper optimization of these parameters improves pollutant degradation, increases mineralization efficiency, reduces energy consumption, and supports the practical application of EAOPs for landfill leachate treatment [5], [7], [9].

5. PERFORMANCE EVALUATION OF ELECTROCHEMICAL ADVANCED OXIDATION PROCESSES (EAOPS) FOR LANDFILL LEACHATE TREATMENT

The performance of Electrochemical Advanced Oxidation Processes (EAOPs) is usually evaluated by measuring their ability to remove pollutants, reduce toxicity, improve biodegradability, and mineralize organic contaminants present in landfill leachate [4], [5]. The treatment efficiency is commonly assessed using parameters such as Chemical Oxygen Demand (COD), Total Organic Carbon (TOC), Biochemical Oxygen Demand (BOD), ammonia nitrogen (NH_4^+–N), color, heavy metals, toxicity, and the removal of emerging contaminants [1], [5], [7].

Many laboratory-scale and pilot-scale studies have shown that EAOPs perform better than conventional treatment methods, especially for mature landfill leachate that contains high concentrations of refractory organic compounds [5], [7], [9]. These processes generate highly reactive oxidizing species, mainly hydroxyl radicals (OH^-), which can effectively degrade complex pollutants into simpler compounds and finally convert them into carbon dioxide, water, and inorganic ions [4], [5].

5.1 Chemical Oxygen Demand (COD) Removal

Chemical Oxygen Demand (COD) is one of the most commonly used parameters for evaluating landfill leachate treatment because it indicates the total amount of oxygen required to chemically oxidize the organic matter present in wastewater [1], [7]. A decrease in COD value indicates that a significant portion of the organic pollutants has been degraded during treatment.

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EAOPs have shown excellent performance in reducing COD due to the continuous generation of hydroxyl radicals and other reactive oxygen species [4], [5]. These oxidants attack complex organic compounds and gradually convert them into smaller molecules before complete mineralization takes place [4], [6].

Among the different EAOP technologies, Electro-Fenton (EF) and Photoelectro-Fenton (PEF) generally provide the highest COD removal because they continuously generate hydroxyl radicals through Fenton reactions [9]. Several studies have reported COD removal efficiencies above 90% for mature landfill leachate under optimized operating conditions [9], [13]. Similarly, anodic oxidation using boron-doped diamond (BDD) electrodes also achieves high COD removal because of its strong oxidation ability and high oxygen evolution potential [5], [10].

The efficiency of COD removal depends on several operating factors, including electrode material, current density, reaction time, solution pH, supporting electrolyte concentration, reactor design, hydraulic retention time, and the initial pollutant concentration [4], [5], [6]. Proper optimization of these parameters improves oxidation efficiency while reducing electrical energy consumption.

Although COD removal is an important indicator of treatment performance, it does not always represent complete mineralization because some partially oxidized intermediate compounds may still remain in the treated wastewater [5], [10]. Therefore, COD analysis is often combined with TOC measurement to evaluate the actual mineralization of organic pollutants.

5.2 Total Organic Carbon (TOC) Removal

Total Organic Carbon (TOC) is another important parameter used to evaluate the efficiency of EAOPs because it directly measures the amount of organic carbon remaining in the treated wastewater [1], [5]. Unlike COD, which measures the oxygen needed for oxidation, TOC indicates how much organic carbon has been completely converted into carbon dioxide. Therefore, TOC is considered a better indicator of pollutant mineralization [4], [5].

EAOPs can achieve high TOC removal through continuous oxidation of both the original pollutants and the intermediate compounds formed during treatment [5], [9]. However, TOC removal usually occurs more slowly than COD reduction because intermediate products such as formic acid, oxalic acid, and acetic acid are more resistant to oxidation [4], [10].

Among the different electrochemical technologies, Photoelectro-Fenton (PEF) often provides the highest TOC removal because the combined electrochemical and photochemical reactions produce a larger amount of hydroxyl radicals [9]. Likewise, anodic oxidation using boron-doped diamond (BDD) electrodes also shows excellent mineralization performance because it continuously generates highly reactive hydroxyl radicals with strong oxidation capability [5], [10].

The degree of TOC removal depends on several factors, including reaction time, current density, electrode material, wastewater composition, and reactor configuration [5], [6]. A higher TOC removal percentage indicates more complete destruction of refractory organic matter and lower residual toxicity in the treated landfill leachate [4], [5].

5.3 Ammonia Oxidation

Ammonia nitrogen (NH_4^+–N) is one of the major pollutants present in landfill leachate, especially in mature leachate. It is mainly produced during the decomposition of proteins and other nitrogen-containing organic materials in municipal solid waste [7], [8]. High concentrations of ammonia are harmful to aquatic organisms and can reduce the overall quality of receiving water bodies [2], [7].

EAOPs remove ammonia through both direct electrochemical oxidation and indirect oxidation by reactive oxygen species generated during the treatment process [5], [6]. During anodic oxidation, ammonia can be converted into harmless nitrogen gas (N_2) through a series of electrochemical reactions [6], [10]. When chloride-containing electrolytes are used, active chlorine species such as hypochlorous acid (HOCl) and hypochlorite ions (OCl^-) are produced, which further improve ammonia removal by indirect oxidation [6], [10].

The main ammonia oxidation pathways include:

- Oxidation of ammonia into nitrogen gas (N_2).
- Formation of nitrate (NO_3^-) and nitrite (NO_2^-) under certain operating conditions.
- Oxidation by hydroxyl radicals (OH^-) and active chlorine species [5], [6].

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The efficiency of ammonia removal depends on several factors, including current density, electrode material, and chloride concentration, reaction time, and solution pH [5], [6]**.** Although the Electro-Fenton process mainly focuses on degrading organic pollutants, combining it with anodic oxidation or other hybrid electrochemical processes can significantly improve ammonia removal while simultaneously reducing COD [5], [9]**.**

5.4 Color Removal

Landfill leachate usually has a dark brown or black color because it contains humic substances, fulvic acids, lignin derivatives, and other high-molecular-weight organic compounds [7], [11]**.** Color removal is an important treatment parameter because it reflects the degradation of refractory organic matter and improves the appearance of the treated wastewater.

EAOPs are highly effective in removing color through the oxidation of aromatic compounds and the breakdown of chromophoric functional groups responsible for light absorption [4], [5]**.** Hydroxyl radicals rapidly attack these colored compounds, resulting in de colorization and gradual mineralization of organic pollutants [4], [10]**.**

Among the different EAOP technologies, Electro-Fenton (EF), Photoelectro-Fenton (PEF), and anodic oxidation using boron-doped diamond (BDD) electrodes have shown excellent color removal performance [5], [9]**.** Under optimized operating conditions, these processes can achieve more than 95% color removal within a relatively short treatment time [9], [13]**.**

The efficiency of color removal depends on factors such as oxidant concentration, reaction time, current density, electrode material, and the composition of landfill leachate [5], [6]**.** In most cases, color disappears before complete mineralization because the chromophoric structures are destroyed earlier than the remaining organic intermediates [4], [5]**.**

5.5 Heavy Metal Removal

Besides organic pollutants, landfill leachate also contains toxic heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), mercury (Hg), zinc (Zn), and arsenic (As) [7], [8]**.** These metals are non-biodegradable and can accumulate in living organisms, causing serious environmental and health problems [2], [7]**.**

Although EAOPs are mainly developed for the degradation of organic contaminants, they also contribute to heavy metal removal through several electrochemical mechanisms **[5], [6]**. These include:

- Electrochemical reduction of metal ions at the cathode.
- Electrocoagulation and precipitation.
- Adsorption of metals onto metal hydroxide flocs.
- Co-precipitation with iron hydroxides.
- Oxidation–reduction reactions that change metal solubility [5], [6], [10]**.**

Hybrid systems that combine electro coagulation with electrochemical oxidation have shown better heavy metal removal because they can simultaneously remove dissolved metal ions and degrade organic pollutants [5], [7]**.**

The efficiency of heavy metal removal depends on several operating parameters, including solution pH, electrode material, applied current, reaction time, hydraulic retention time, and the initial concentration of metal ions [5], [6]**.** Proper optimization of these factors improves metal removal efficiency and helps produce treated wastewater that meets environmental discharge standards [2], [5]**.**

5.6 Degradation of Emerging Contaminants

In recent years, landfill leachate has been found to contain many emerging contaminants that are difficult to remove using conventional biological treatment methods. These contaminants include pharmaceuticals, antibiotics, hormones, endocrine-disrupting compounds (EDCs), pesticides, surfactants, dyes, personal care products, per- and poly fluoro alkyl substances (PFAS), and micro plastics [5], [9], [12].

Electrochemical Advanced Oxidation Processes (EAOPs) have shown good potential for removing these persistent pollutants because they produce highly reactive hydroxyl radicals (OH^-) during the treatment process. These radicals attack complex organic

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molecules through reactions such as hydroxylation, electron transfer, hydrogen abstraction, aromatic ring opening, and cleavage of carbon–heteroatom bonds, leading to their breakdown into smaller and less harmful compounds [4], [5].

Several studies have reported that Electro-Fenton, anodic oxidation, and hybrid EAOP systems can effectively degrade a wide range of emerging contaminants present in landfill leachate. Besides reducing pollutant concentration, these processes also decrease toxicity and improve the biodegradability of the treated wastewater, making further treatment easier [5], [9], [10].

However, complete mineralization of some highly stable compounds, especially fluorinated substances such as PFAS, remains a major challenge because of their strong chemical bonds and resistance to oxidation [9]. Therefore, current research is mainly focused on developing better electrode materials and combining EAOPs with technologies such as photo catalysis, biological treatment, membrane filtration, and other hybrid processes to improve degradation efficiency and reduce operating costs [5], [9], [10].

5.7 Comparative Performance Analysis

Different Electrochemical Advanced Oxidation Processes (EAOPs) have their own advantages and limitations. The selection of a suitable process mainly depends on the characteristics of the landfill leachate, the required treatment efficiency, operating cost, and discharge standards [4], [5].

Anodic oxidation (AO) is one of the simplest EAOPs and requires only a small amount of chemicals. When boron-doped diamond (BDD) electrodes are used, AO can achieve excellent mineralization of refractory organic pollutants because of the high production of hydroxyl radicals. However, its large-scale application is often limited by high electrical energy consumption and the high cost of BDD electrodes [4], [5], [10].

The Electro-Fenton (EF) process is widely recognized for its high oxidation efficiency and excellent COD removal performance. It continuously regenerates Fe^{2+} ions during the reaction, which helps produce hydroxyl radicals without adding large amounts of chemicals. Under optimized operating conditions, EF has reported COD removal efficiencies of more than 90% for landfill leachate [5], [9]. Its main limitation is that it works best under acidic conditions (pH 2.5–3.5), which may require pH adjustment before and after treatment [4], [9].

Photoelectro-Fenton (PEF) combines the Electro-Fenton process with UV or solar light irradiation. Light helps regenerate Fe^{2+} from Fe^{3+}, increasing hydroxyl radical production and improving pollutant mineralization. As a result, PEF often achieves higher COD and TOC removal than the conventional EF process. However, the need for an external light source increases the overall operating cost and system complexity [4], [5], [9].

The Electro-Peroxone (EP) process combines electrochemically generated hydrogen peroxide with ozone to produce more hydroxyl radicals. This combined process is highly effective for degrading refractory organic compounds and emerging contaminants. Although EP provides faster oxidation and higher treatment efficiency than ozonation alone, the requirement for ozone generation equipment increases both capital and maintenance costs [5], [10].

Recently, hybrid EAOP technologies have received considerable attention because they combine electrochemical oxidation with biological treatment, membrane filtration, electro coagulation, photo catalysis, or per sulfate activation. These integrated systems generally achieve better pollutant removal, lower energy consumption, reduced sludge production, and improved overall treatment efficiency compared with individual processes [5], [9], [10].

Overall, no single EAOP is suitable for every type of landfill leachate. The choice of treatment technology depends on several factors, including leachate composition, pollutant concentration, treatment objectives, available infrastructure, operating cost, and environmental regulations. Selecting the appropriate EAOP based on these factors can improve treatment efficiency and make the process more economical for large-scale applications [4], [5], [9].

5.8 Kinetic Evaluation

Kinetic analysis is an important part of evaluating the performance of Electrochemical Advanced Oxidation Processes (EAOPs). It helps explain how pollutants are degraded during treatment and provides useful information for reactor design, process optimization, and large-scale application [4], [5]. In most studies, the degradation of organic pollutants in landfill leachate is described using pseudo-first-order or pseudo-second-order kinetic models**,** depending on the treatment conditions and the type of contaminants present [5], [9].

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For many landfill leachate pollutants, the degradation process follows a pseudo-first-order kinetic model, which is expressed as:

ln (C0Ct)=kt\ln \left(\frac{C_0}{C_t}\right)=ktln(CtC0)=kt

Where:

- C_0 = initial pollutant concentration,
- C_t = pollutant concentration at time *t*,
- k = apparent first-order rate constant (min^{-1}),
- t = reaction time (min).

The value of the rate constant (k) indicates the speed of pollutant degradation. A higher k value means that oxidation occurs more rapidly, resulting in better treatment efficiency [4], [5].

The reaction rate of EAOPs is influenced by several operating parameters, such as the amount of hydroxyl radicals produced, electrode material, applied current density, solution pH, temperature, wastewater composition, and mass transfer inside the reactor [4], [5], [9]. Proper optimization of these factors can significantly improve pollutant degradation and mineralization.

Besides kinetic models, the performance of EAOPs is also evaluated using several other parameters. These include current efficiency (CE)**,** electrical energy per order (EEO)**,** specific energy consumption (kWh m^{-3})**,** TOC removal efficiency**,** and the BOD/COD ratio, which indicates the improvement in wastewater biodegradability after treatment [4], [5], [12]. These parameters help compare different electrochemical treatment methods and determine their technical and economic feasibility.

Overall, kinetic analysis provides valuable information for selecting suitable operating conditions, improving reactor performance, reducing energy consumption, and supporting the scale-up of EAOPs from laboratory studies to full-scale landfill leachate treatment plants [5], [9].

Experimental studies reported in the literature show that EAOPs are highly effective for treating landfill leachate. These processes achieve high removal efficiencies for COD, TOC, ammonia, color, heavy metals, and emerging contaminants, while also reducing toxicity and improving wastewater biodegradability [4], [5], [9]. Continuous progress in electrode materials, reactor design, and hybrid treatment technologies is expected to further improve the efficiency, sustainability, and practical application of EAOPs in future landfill leachate treatment systems [5], [10].

6. ADVANTAGES, LIMITATIONS, AND FUTURE PERSPECTIVES OF ELECTROCHEMICAL ADVANCED OXIDATION PROCESSES (EAOPS)

Electrochemical Advanced Oxidation Processes (EAOPs) are considered one of the most effective technologies for treating landfill leachate because they can remove pollutants that are difficult to degrade using conventional treatment methods. These processes produce highly reactive oxygen species, especially hydroxyl radicals (OH^{-}), which can oxidize and break down complex organic pollutants into simpler and less harmful compounds [4], [5]. EAOPs are also environmentally friendly because they generate oxidizing agents directly inside the reactor, reducing the need for additional chemicals and minimizing secondary pollution [5], [6].

Another important advantage of EAOPs is their flexibility. They can be used alone or combined with biological treatment, membrane filtration, photo catalysis, or electro coagulation to improve treatment efficiency [5], [9]. Several studies have reported high removal efficiencies for chemical oxygen demand (COD), total organic carbon (TOC), color, ammonia, and many emerging contaminants when operating conditions are properly optimized [5], [9], [10]. These benefits make EAOPs a suitable option for treating mature landfill leachate, which usually contains high concentrations of refractory organic compounds.

Although EAOPs have many advantages, some limitations still restrict their large-scale application. One of the main challenges is the high electrical energy requirement, especially when high current densities or long treatment times are used [5], [6]. The cost of advanced electrode materials, such as boron-doped diamond (BDD), is also relatively high, increasing the overall treatment cost [5], [10]. In addition, some electrodes may lose their activity over time because of fouling, corrosion, or passivation, which can reduce treatment efficiency and increase maintenance requirements [5], [6].

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Another issue is the possible formation of unwanted by-products. When chloride-containing electrolytes are used, active chlorine species may be produced, which can lead to the formation of chlorinated organic compounds if operating conditions are not properly controlled [6], [12]. Furthermore, some EAOPs, such as the Electro-Fenton process, work efficiently only under acidic conditions (pH 2.5–3.5), making pH adjustment necessary before and after treatment [4], [9]. These additional treatment steps increase both operational complexity and overall cost.

Future research is mainly focused on improving the efficiency and economic feasibility of EAOPs. Researchers are developing low-cost and durable electrode materials with higher catalytic activity and longer service life [5], [10]. Hybrid treatment systems that combine EAOPs with biological processes, membrane technologies, photo catalysis, or electro coagulation are also being investigated to achieve better pollutant removal while reducing energy consumption [5], [9]. In addition, the use of renewable energy sources such as solar and wind power can help lower electricity costs and improve the sustainability of electrochemical treatment systems [9].

Recent developments in artificial intelligence (AI), machine learning, and real-time monitoring are expected to further improve reactor operation by optimizing current density, reaction time, pH, and energy consumption automatically [5], [9]. More pilot-scale and full-scale studies, along with techno-economic and life-cycle assessments, are still needed to evaluate the practical performance of EAOPs under real operating conditions [5]. With continued improvements in reactor design, electrode materials, and process integration, EAOPs are expected to become an important technology for sustainable landfill leachate treatment in the future [4], [5], [9].

6.1 Advantages of Electrochemical Advanced Oxidation Processes (EAOPs)

Electrochemical Advanced Oxidation Processes (EAOPs) have several advantages over conventional wastewater treatment methods, making them a suitable option for treating landfill leachate, especially mature leachate that contains high concentrations of non-biodegradable and persistent pollutants [4], [5]. These processes are highly effective because they can degrade pollutants instead of simply transferring them from one phase to another. The major advantages of EAOPs are discussed below.

High Oxidation Efficiency

One of the main advantages of EAOPs is their ability to produce highly reactive hydroxyl radicals (OH^-), which have a very high oxidation potential of about 2.8 V [12]. These radicals can react with a wide variety of organic pollutants without much selectivity, including humic substances, phenolic compounds, dyes, pharmaceuticals, pesticides, and endocrine-disrupting chemicals [4], [5]. As a result, EAOPs achieve high removal efficiencies for chemical oxygen demand (COD), total organic carbon (TOC), color, and other toxic organic pollutants [5], [9].

Complete or Near-Complete Mineralization

Unlike adsorption or membrane filtration, which only transfer pollutants from water to another medium, EAOPs can break down organic contaminants into harmless end products such as carbon dioxide (CO_2), water (H_2O), and inorganic ions [4], [5]. This process is known as mineralization and helps reduce secondary pollution. It also lowers the amount of sludge produced, making waste management easier and more environmentally friendly [5].

In Situ Generation of Oxidants

Another important benefit of EAOPs is that oxidizing species are generated directly inside the electrochemical reactor. There is no need to continuously add or store hazardous chemicals because hydroxyl radicals and other reactive oxygen species are produced during the electrochemical reaction itself [5], [6]. This makes the process safer, reduces chemical consumption, and simplifies plant operation.

Operational Flexibility

EAOPs can be used to treat different types of wastewater with varying pollutant concentrations. Their performance can be easily adjusted by changing operating conditions such as current density, applied voltage, reaction time, pH, electrode material, and electrolyte concentration [5], [6]. This flexibility makes EAOPs suitable for both industrial wastewater and landfill leachate treatment.

Low Sludge Production

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Compared with conventional treatment methods such as coagulation and chemical precipitation, EAOPs produce much less secondary sludge [7], [10]. Since pollutants are mainly degraded rather than separated, the cost of sludge handling and disposal is reduced, making the treatment process more sustainable.

Easy Integration with Other Treatment Methods

EAOPs can be combined with biological treatment, electro coagulation, membrane filtration, adsorption, and photo catalysis to improve overall treatment performance [5], [9]. These hybrid systems often achieve higher pollutant removal, better biodegradability, lower energy consumption, and improved treatment efficiency compared to using a single process alone.

Automation and Renewable Energy Compatibility

Electrochemical treatment systems are easy to automate because their operating conditions can be controlled using sensors and programmable control systems [5]. Since electricity is the main energy source, EAOPs can also be powered by renewable energy such as solar or wind power. This helps reduce operating costs and greenhouse gas emissions while supporting sustainable wastewater treatment practices [9].

Overall, EAOPs provide high oxidation efficiency, low sludge production, operational flexibility, and good compatibility with other treatment technologies. These advantages make them one of the most promising options for efficient and sustainable landfill leachate treatment [4], [5], [9].

6.2 Limitations of Electrochemical Advanced Oxidation Processes (EAOPs)

Although Electrochemical Advanced Oxidation Processes (EAOPs) have many advantages, they still face several technical and economic challenges that limit their large-scale use for landfill leachate treatment [5], [6]. Some of the major limitations are discussed below.

High Electrical Energy Consumption

One of the main drawbacks of EAOPs is their high electricity requirement. The amount of energy consumed depends on factors such as current density, treatment time, wastewater composition, and reactor design [5], [6]. Landfill leachate usually contains a high concentration of refractory organic compounds, which often require longer treatment times and higher current densities. As a result, operating costs increase. Therefore, improving energy efficiency and reducing power consumption remain important research areas [5], [9].

High Cost and Limited Lifetime of Electrodes

The performance of EAOPs largely depends on the electrode material used. Advanced electrodes such as boron-doped diamond (BDD) provide excellent oxidation efficiency and high pollutant removal, but they are expensive to manufacture and install [5], [10]. During long-term operation, electrodes may also experience fouling, corrosion, passivation, or mechanical damage, which reduces their efficiency and increases maintenance and replacement costs [6], [10].

Requirement for Acidic Conditions

Some EAOPs, especially the Electro-Fenton process, work best under acidic conditions with a pH range of about 2.5–3.5 [4], [9]. Therefore, the wastewater often needs pH adjustment before and after treatment. This increases the consumption of chemicals, adds extra treatment steps, and raises the overall operating cost. Maintaining the required pH can also become difficult in large-scale treatment plants.

Formation of Oxidation By-products

Although EAOPs are effective in degrading organic pollutants, complete mineralization is not always achieved. During the treatment process, some intermediate compounds may be formed, and these can sometimes be more toxic than the original pollutants if the reaction is incomplete [5], [12]. In addition, when chloride-containing electrolytes are used, active chlorine species may produce chlorinated organic compounds, chlorate, and perchlorate under certain operating conditions [6]. Proper control of operating parameters is therefore necessary to reduce the formation of unwanted by-products.

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Challenges in Large-Scale Application

Most studies on EAOPs have been carried out at laboratory or pilot scale using small amounts of landfill leachate [5], [9]. Their application at full industrial scale is still limited because of challenges related to reactor design, mass transfer, hydraulic performance, electrode durability, and treatment cost. More pilot-scale demonstrations and long-term field studies are needed before EAOPs can be widely adopted for commercial landfill leachate treatment [5].

Variation in Landfill Leachate Composition

The composition of landfill leachate changes with landfill age, waste type, climate, rainfall, and operating conditions [7], [8]. Because of these variations, a treatment system that performs well under one condition may not be equally effective under another. Therefore, EAOPs often require careful optimization of operating conditions, and in many cases, they are combined with other treatment methods to achieve consistent performance [5], [9].

Overall, EAOPs are highly effective for treating landfill leachate, but issues such as high energy consumption, expensive electrode materials, pH requirements, by-product formation, and scale-up challenges still need to be addressed. Continued research on low-cost electrode materials, energy-efficient reactors, and hybrid treatment systems is expected to overcome these limitations and improve the practical application of EAOPs in the future [5], [9], [10].

6.3 Future Perspectives

Continuous progress in electrochemical engineering, nanotechnology, materials science, and process automation is expected to improve the performance of Electrochemical Advanced Oxidation Processes (EAOPs) for landfill leachate treatment. Many researchers are working on developing more efficient, economical, and environmentally friendly systems for large-scale applications [5], [14].

Advanced Electrode Materials

One of the main areas of research is the development of low-cost, durable, and highly conductive electrode materials. New materials such as graphene-based electrodes, carbon nano tubes, mixed metal oxides; doped diamond films, conductive polymers, and nano composite electrodes have shown good potential. These materials can improve hydroxyl radical generation, increase pollutant degradation, reduce energy consumption, and extend electrode life [5], [10], [14].

Hybrid Treatment Technologies

Combining EAOPs with other treatment methods is another promising approach. Hybrid systems that integrate biological treatment, membrane bioreactors, photo catalysis, and electro coagulation, per sulfate activation, adsorption, and membrane filtration can achieve better removal of organic pollutants, nutrients, and toxic compounds. These combined systems also improve biodegradability while reducing operating costs and sludge production [5], [8], [9].

Renewable Energy Integration

Since EAOPs mainly require electrical energy, they can be operated using renewable energy sources such as solar and wind power. Renewable-energy-driven electrochemical systems can reduce electricity costs, lower greenhouse gas emissions, and make wastewater treatment more sustainable, especially in remote and rural areas [4], [5].

Artificial Intelligence and Process Automation

The use of artificial intelligence (AI), machine learning (ML), and smart monitoring systems is increasing in wastewater treatment. These technologies can continuously monitor treatment conditions, predict system performance, optimize operating parameters, reduce energy consumption, and detect equipment problems at an early stage. As a result, the treatment process becomes more reliable and efficient [5].

Resource Recovery and Circular Economy

Future landfill leachate treatment systems are expected to focus not only on pollution control but also on resource recovery. EAOPs can be integrated with technologies for water reuse, nutrient recovery, hydrogen production, and recovery of valuable

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chemicals. This approach supports the concept of a circular economy by reducing waste and improving resource utilization [5], [14].

Pilot-Scale and Industrial Applications

Although many laboratory studies have reported excellent results, more pilot-scale and full-scale studies are still needed. Future research should focus on long-term operation, reactor design, economic analysis, life-cycle assessment, and environmental impact evaluation. These studies will help demonstrate the practical feasibility of EAOPs for large-scale landfill leachate treatment [5], [8], [9].

Overall, EAOPs have strong potential to become one of the leading technologies for landfill leachate treatment. Continued improvements in electrode materials, reactor design, renewable energy integration, and intelligent process control are expected to increase treatment efficiency, lower operating costs, and support the sustainable management of landfill leachate in the future [5], [10], [14].

7. CONCLUSIONS

Landfill leachate is a complex wastewater produced from municipal solid waste (MSW) landfills. It contains high concentrations of organic matter, ammonia, heavy metals, dissolved salts, and different types of emerging contaminants. The composition of leachate changes with landfill age and environmental conditions, making its treatment difficult. Conventional treatment methods are often effective for biodegradable pollutants, but they are less efficient in removing refractory organic compounds and other persistent contaminants. Therefore, advanced treatment technologies are required for effective landfill leachate treatment [7], [8], [9].

Among the available advanced treatment methods, Electrochemical Advanced Oxidation Processes (EAOPs) have shown excellent potential because they generate highly reactive oxidizing species, especially hydroxyl radicals ($OH^{\cdot}$), during electrochemical reactions. These radicals can effectively degrade complex organic pollutants and improve the overall quality of treated wastewater. Different EAOPs, including anodic oxidation, Electro-Fenton, Photoelectro-Fenton, Electro-Peroxone, and hybrid electrochemical systems, have achieved high removal efficiencies for COD, TOC, color, and several toxic and emerging contaminants under optimized operating conditions [4], [5], [6], [14].

The performance of EAOPs depends on several operating parameters such as electrode material, current density, solution pH, supporting electrolyte, reaction time, and reactor design. Among different electrode materials, boron-doped diamond (BDD) electrodes have shown the best oxidation performance because they produce a large amount of hydroxyl radicals and have a high oxygen evolution potential. Proper optimization of these operating conditions can improve pollutant removal while reducing energy consumption and operating costs [5], [6], [10].

Although EAOPs have many advantages, some limitations still need to be addressed before they can be widely used on an industrial scale. High electricity consumption, the high cost of advanced electrode materials, possible formation of oxidation by-products, and difficulties in scaling up laboratory studies are some of the major challenges. Further improvements in reactor design, electrode development, renewable energy integration, and process optimization are needed to overcome these limitations [5], [6], [10].

Future research should focus on developing low-cost and durable electrode materials, improving hybrid treatment systems, applying artificial intelligence for process control, and using renewable energy sources to reduce operational costs. More pilot-scale and full-scale studies, along with life-cycle assessment and techno-economic analysis, are also necessary to evaluate the practical application of EAOPs in real wastewater treatment plants [5], [8], [14].

In conclusion, Electrochemical Advanced Oxidation Processes are among the most promising technologies for landfill leachate treatment. Their high oxidation ability, excellent pollutant removal efficiency, and compatibility with other treatment methods make them suitable for treating complex wastewaters. With continued research and technological improvements, EAOPs are expected to play an important role in sustainable landfill leachate management and future wastewater treatment systems [4], [5], [10], [14].

8. CONCLUDING REMARKS: CLASSIFICATION AND SELECTION, PROPERTY CHARACTERIZATION, INDUSTRIAL TRENDS, AND FUTURE RESEARCH PRIORITIES

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8.1 Classification and Selection of EAOPs

Electrochemical Advanced Oxidation Processes (EAOPs) are a group of advanced wastewater treatment technologies that remove pollutants by generating strong oxidizing species through electrochemical reactions. Based on the method of oxidant generation and reactor design, EAOPs are classified into anodic oxidation (AO), Electro-Fenton (EF), Photoelectro-Fenton (PEF), Electro-Peroxone (EP), electrochemical per sulfate activation, and different hybrid electrochemical systems. Hybrid systems combine electrochemical oxidation with biological treatment, photo catalysis, membrane filtration, or electro coagulation to improve treatment efficiency [4], [5], [6].

The selection of a suitable EAOP mainly depends on the characteristics of the landfill leachate and the treatment requirements. Factors such as pollutant concentration, biodegradability, treatment efficiency, operating cost, energy consumption, and discharge standards should be considered before selecting a treatment process [7], [8].

Anodic oxidation using boron-doped diamond (BDD) electrodes is widely used for landfill leachate containing high concentrations of refractory organic pollutants because it provides excellent mineralization efficiency. Electro-Fenton is highly effective for wastewater containing a large amount of dissolved organic matter, while Photoelectro-Fenton further improves pollutant degradation by using light to regenerate ferrous ions. Electro-Peroxone is suitable for the rapid oxidation of persistent pollutants, whereas hybrid EAOPs provide better overall performance by combining different treatment methods and reducing energy consumption [4], [5], [6], [9].

Therefore, there is no single EAOP that is suitable for every type of landfill leachate. The treatment method should be selected based on wastewater characteristics, treatment objectives, operating cost, energy efficiency, environmental impact, and overall process performance [5], [7].

8.2 Property Characterization

Proper characterization of landfill leachate is essential before designing an electrochemical treatment system. The properties of landfill leachate change depending on landfill age, waste composition, weather conditions, moisture content, and the stage of waste decomposition. Young landfill leachate usually contains a high amount of biodegradable organic matter and has a high BOD/COD ratio. In contrast, mature landfill leachate contains more refractory organic compounds, ammonia, dissolved salts, heavy metals, and emerging contaminants, making it more difficult to treat [7], [8], [15].

Several physicochemical parameters are commonly analyzed to evaluate landfill leachate and the performance of EAOPs. These include pH, electrical conductivity, oxidation-reduction potential (ORP), Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), Total Organic Carbon (TOC), ammonia nitrogen (NH_4^+–N), Total Dissolved Solids (TDS), Total Suspended Solids (TSS), color, turbidity, heavy metal concentration, toxicity, and biodegradability index [1], [7].

Advanced analytical techniques are also used to study pollutant degradation and electrode properties. Common techniques include Gas Chromatography–Mass Spectrometry (GC–MS), Liquid Chromatography–Mass Spectrometry (LC–MS), Fourier Transform Infrared Spectroscopy (FTIR),

X-ray Photoelectron Spectroscopy (XPS), Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), X-ray Diffraction (XRD), Raman Spectroscopy, and Electrochemical Impedance Spectroscopy (EIS). These methods help identify degradation products, evaluate electrode surfaces, and understand electrochemical reaction mechanisms [5], [6], [10].

A detailed analysis of landfill leachate properties helps in selecting suitable operating conditions, improving reactor design, optimizing treatment efficiency, and predicting the performance of EAOPs in large-scale wastewater treatment systems. Therefore, proper characterization plays an important role in the successful application of electrochemical treatment technologies [5], [8], [10].

8.3 Industrial Trends

Electrochemical Advanced Oxidation Processes (EAOPs) are gradually moving from laboratory research to pilot-scale and industrial applications because of their high efficiency in treating landfill leachate. Strict environmental regulations and the need for better wastewater treatment have encouraged industries to develop advanced electrochemical systems that can remove pollutants more effectively while reducing environmental impacts [1],[2].

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One of the major industrial developments is the commercial use of boron-doped diamond (BDD) electrodes because of their excellent oxidation performance and long service life. Other important improvements include the use of dimensionally stable anodes (DSA), three-dimensional electrode reactors, and carbon-based cathodes, which increase pollutant removal while lowering energy consumption. Many treatment plants are also combining EAOPs with membrane bioreactors (MBRs), reverse osmosis (RO), and continuous-flow reactors to improve overall treatment efficiency [3],[4].

The use of digital technologies is also increasing in electrochemical wastewater treatment. Artificial intelligence (AI), machine learning (ML), Internet of Things (IoT)-based monitoring systems, digital twins, and automatic process control are being used to monitor treatment performance, optimize operating conditions, reduce energy use, and predict maintenance requirements. At the same time, renewable energy sources such as solar and wind power are being integrated with EAOP systems to make the treatment process more sustainable and cost-effective [5],[6].

Another important trend is the shift from only removing pollutants to recovering useful resources. Modern wastewater treatment plants are focusing on water reuse, nutrient recovery, hydrogen production, and resource recovery based on circular economy principles. This approach not only protects the environment but also improves the overall sustainability of landfill leachate management [7],[8].

8.4 Future Research Priorities

Although EAOPs have shown excellent performance for landfill leachate treatment, there are still several challenges that need further research before these technologies can be widely used at the industrial scale [2],[5].

One of the main research areas is the development of low-cost, durable, and environmentally friendly electrode materials with high catalytic activity and longer service life. Researchers are also working on nano structured electrodes that can produce more hydroxyl radicals while using less electrical energy [3],[4].

Another important direction is the development of hybrid treatment systems. Combining EAOPs with biological treatment, photo catalysis, membrane filtration, adsorption, electro coagulation, and per sulfate activation can improve pollutant removal, increase mineralization efficiency, and reduce operating costs and secondary pollution [6],[7].

Future studies should also focus on identifying oxidation intermediates and understanding degradation pathways to ensure complete mineralization of pollutants. In addition, more work is needed to evaluate the long-term environmental effects of oxidation by-products. Standard methods for kinetic analysis, reactor performance evaluation, energy consumption, and life-cycle assessment should also be developed to allow proper comparison of different EAOP technologies [1],[5].

More pilot-scale and full-scale studies are required to confirm laboratory results under real operating conditions. These studies should include economic analysis, life-cycle assessment, carbon footprint evaluation, and resource recovery potential to determine the practical feasibility of EAOPs for industrial applications [2],[8].

The use of artificial intelligence, machine learning, computational fluid dynamics (CFD), smart monitoring systems, and renewable energy technologies is expected to further improve process control, reduce treatment costs, and increase the reliability of electrochemical treatment systems [5],[6].

Overall, EAOPs have become one of the most promising technologies for landfill leachate treatment. Continued research in electrochemistry, environmental engineering, materials science, nanotechnology, and digital technologies will help overcome current limitations and support the large-scale use of EAOPs for sustainable wastewater treatment and circular economy applications [1]–[8].

Conflict of Interest

The authors declare that there are no known financial, personal, professional, or institutional conflicts of interest that could have influenced the work reported in this manuscript. The authors further confirm that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References [9]–[25] are very helpful for my literature review. They cover key topics related to wastewater treatment—such as EAOPs, electrocoagulation, and electro-Fenton—and have proven truly valuable in supporting our research.