Journal Homepage: http://ijcpe.uobaghdad.edu.iq
Iraqi Journal of Chemical and Petroleum Engineering
Vol. 26 No. 3 (September 2025) 63 – 83
EISSN: 2618-0707, PISSN: 1997-4884

Challenges and future directions in photoelectro-Fenton techniques: A comprehensive review of emerging applications and innovations

Ihsan H. Dakhil [a, b], **Ammar S. Abbas** [a, *]

a Chemical Engineering Department, College of Engineering, University of Baghdad, Baghdad, Iraq
b Chemical Engineering Department, College of Engineering, Al-Muthanna University, Samawa, Iraq

Abstract

This comprehensive review examines the fundamental principles and practical applications of heterogeneous electrochemical wastewater treatment utilizing Fenton's reactions. The fundamental equations involved in generating hydroxyl-free radicals in electro-Fenton and photoelectro-Fenton processes have been reviewed. Photoelectro-Fenton processes have been proven to be the most effective methods for mineralizing and degrading pollutants in wastewater. The primary focus is on understanding the limitations of hybrid Fenton processes and proposing practical solutions to address these challenges. Additionally, the study evaluated the significance of electrode configuration development and light penetration enhancement in promoting hydrogen peroxide production and enhancing hydroxyl radical generation. These improvements contribute to the enhanced degradation and mineralization of contaminants in groundwater. A comparative analysis of electrode materials, novel reactor configurations, and operating conditions demonstrates the relationship between preparation methods and treatment efficiency. Research gaps for improving the photoelectro-Fenton process are identified, with suggestions for future work. Studies have shown that internal light irradiation leads to higher removal efficiency compared to external lighting systems with the same light source power. The most important recommendations were utilizing multi-electrode stacked reactors to reduce energy consumption, enhancing current efficiency, the shape of the electrodes also plays a vital role in increasing light exposure on the photoanode surfaces, and conducting long-term experiments with various contaminants to demonstrate the reactor's stability, efficiency, and efficacy in treating industrial wastewater.

Keywords: Electrode arrangements; Novel reactors; Fenton hybrid; Doping methods; Fenton's challenges.

Received on 19/05/2025, Received in Revised Form on 15/07/2025, Accepted on 22/07/2025, Published on 30/09/2025

https://doi.org/10.31699/IJCPE.2025.3.7

1- Introduction

Water pollution represents the most significant environmental and public health challenge facing humanity in the 21st century. Due to the increasing discharge of industrial effluents, agricultural intensification, and rapid urbanization, a broad spectrum of complex pollutants has been released into the aquatic environment globally [1]. These pollutants span a wide range of compounds that include traditional pollutants (organic and inorganic matter, nutrients, pathogens), heavy metals, industrial chemicals, agricultural discharges, pharmaceuticals and personal care products, endocrine-disrupting compounds, microplastics, and a long list of emerging pollutants of concern [2, 3]. The occurrence of these pollutants, even in traces in the aquatic environment, could disrupt marine life and human drinking water quality as well, and present a high risk to human health via bio-accumulation and possible toxicological effects [4].

Traditional wastewater techniques have been applied to the treatment of industrial wastewater pollutants, including adsorption [5, 6], coagulation [7], sedimentation [8], ion exchange membrane [9], multilayered membrane [10] and biological methods [11]. These methods have been extensively developed to remove organic and inorganic pollutants such as dyes, pharmaceuticals, and heavy metals from industrial wastewater [12, 13]. However, these conventional treatment methods are always inefficient in treating resistant compounds, such as recalcitrant compounds, which have complex molecular structures, high stability, and low biodegradability [14]. To overcome these drawbacks, extensive efforts have been made to develop advanced treatment techniques that can degrade or mineralize recalcitrant contaminants for the protection of water quality, as well as the use of water recycling for agriculture and industrial uses [15, 16].

Advanced oxidation processes (AOPs) have been identified as the most promising technology for overcoming these challenging treatment issues. AOPs are involved in the production of highly reactive oxygen species, hydroxyl radical ($^{\bullet}OH$) in particular, with

---

*Corresponding Author: Email: ammarabbas@coeng.uobaghdad.edu.iq powerful oxidative strength (E° = 2.8 V vs. SHE) and unselective oxidation on organic species [17]. The high oxidation power of the hydroxyl radical allows it to attack most organic molecules, and a succession of oxidative reactions occurs to turn complex pollutants into smaller and more biodegradable molecules or to achieve their complete mineralization to CO_2, H_2O, and inorganic ions [18]. This versatility makes AOPs particularly valuable for treating wastewater containing biorefractory contaminants that resist conventional wastewater treatment. Different AOPs have already been developed, such as Fenton and Fenton-like oxidation [19], ozonation [20], photocatalytic [21, 22], and electrochemical oxidation [23]. These treatments proved to work effectively against organic pollutants in wastewater [24-27]. The use of combined AOPs for treating wastewater has been researched, showing a high potential for removing organic pollutants [28]. As a result, hybrid AOPs may provide a promising approach for economic and sustainable wastewater treatment.

The Fenton process can be considered the most prominent electrochemical advanced oxidation process that has attracted attention in recent decades [29]. This process gained more attention due to its simplicity and effectiveness for wastewater treatment. The classic Fenton reaction involves catalytic decomposition of hydrogen peroxide by ferrous ion to produce hydroxyl radicals ($^\bullet$OH) in an acidic medium, as shown in Eq. 1 [30].

$$\mathrm{Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + OH^- + {}^\bullet OH} \quad (1)$$

The production of hydroxyl radicals, a second highly oxidizing agent after Fluorine, will degrade and mineralize organic contaminants [31]. In the classic Fenton process, it performs best under acidic conditions (pH 2-3), allowing iron to remain physically stable and catalytically active [32]. However, the conventional Fenton process has several associated limitations, including pH correction, continuous iron dosing, and sludge disposal [33]. Various modifications and combinations have been investigated to address these limitations and enhance the Fenton treatment process. Among these technologies, electrochemical advanced oxidation processes (EAOPs) are among the most promising, as they combine electrochemical technology with Fenton chemistry to develop treatment systems that are more effective and environmentally friendly.[34]. The electro-Fenton (EF) process is a typical example of this process, where H_2O_2 is generated at the cathode. H_2O_2 generation occurs electrochemically; therefore, there is no requirement to add H_2O_2 externally and store it, which adds to the safety factor and potentially lowers operating costs [35].

Several challenges still need to be addressed regarding the EF approach. In EF, hydrogen peroxide generation is restricted by oxygen diffusion through the water. The current efficiency at low pH (pH 2-3) is also reduced [36]. However, it is energy-consuming, and efficiency depends on the cathode material, current density, oxygen concentration, and solution conductivity. The EF process has been coupled with light irradiation using a PEF technique to address these drawbacks. PEF could be considered a relatively new hybrid approach with both ecological and economic advantages, in conjunction with surface photocatalysis and EF. It is very promising for its applications in larger units [37]. In the PEF system, hydrogen peroxide is produced continuously in situ on the cathode via the oxygen reduction, and iron ion acts as the catalyst of the Fenton reaction [38]. Simultaneously, UV-irradiation promotes the photo-reduction of Fe^{3+} to Fe^{2+}, accelerating the catalytic cycle and potentially leading to the direct photolysis of intermediate compounds and complexes. The superiority of PEF over other AOPs has been demonstrated for a remarkable diversity of water pollutants. Comprehensive studies have shown its effectiveness for treating pharmaceutical compounds (antibiotics, analgesics, anti-inflammatory compounds), personal care products, industrial chemicals (dyes, surfactants, pesticides), phenolic compounds, and various emerging contaminants [39]. Despite the promising aspects of PEF technology, several challenges hinder its widespread implementation in full-scale wastewater treatment facilities. These include energy consumption concerns, complexity of operation, difficulty of light irradiation, electrode stability, optimal reactor configuration, and process scalability for large-scale applications [40]. Addressing these challenges requires innovative approaches in electrode materials, reactor configurations, and process optimization.

Electrode materials constitute another critical aspect of PEF systems, influencing both process efficiency and long-term stability. Anode materials must exhibit high oxygen evolution overpotential, good conductivity, and exceptional resistance to corrosion under oxidizing conditions. While boron-doped diamond (BDD) electrodes have shown excellent performance due to their wide electrochemical window and weak adsorption properties, their high cost has motivated research into alternative materials such as mixed metal oxides, carbon-based electrodes, and dimensionally stable anodes [41]. Similarly, cathode development focuses on materials with high selectivity for the two-electron oxygen reduction to H_2O_2, with carbon-based materials (such as graphite, carbon felt, and carbon-PTFE composites) and gas-diffusion electrodes showing particular promise [42]. Mass transfer limitations represent another significant challenge in PEF systems. The efficiency of pollutant degradation depends on the effective transport of reactants (O_2, Fe^{2+}/Fe^{3+}, and target pollutants) to reaction sites. Innovative reactor designs incorporating features such as turbulence promoters, enhanced mixing mechanisms, and optimized electrode configurations can improve mass transfer characteristics and overall treatment performance [43]. Nanotechnology integration represents yet another frontier in PEF research. Nanomaterials can enhance process efficiency through various mechanisms, including improved catalytic activity, increased surface area for reactions, enhanced light absorption, and superior electron transfer properties.

Nanostructured electrodes and composite nanomaterials have shown promising results in preliminary studies, though questions regarding long-term stability and potential environmental impacts require careful consideration [44].

According to the Scopus database, a search was conducted for scientific papers focusing on removing persistent organic pollutants (POPs) from simulated and real wastewater up to May 2025. The search used the keywords "photoelectron-Fenton" and "persistent organic pollutants within “title, abstract, and keywords.” The search found 21 documents, including 14 articles, four reviews, and 2 book chapters. A comprehensive study of the hybrid Fenton processes for degrading wastewater pollutants has become essential. Exploring novel reactor shapes, electrode fabrication materials, electrode arrangement, and optimal doping techniques to enhance electrode specifications. Based on our knowledge, this aspect remains unexplored in detail.

This comprehensive review aims to provide a detailed analysis of the current state of PEF technology, with a particular focus on recent advances in electrode materials, electrode arrangements, reactor configurations, and operational parameters that enhance the process efficiency of degrading refractory organic pollutants. This study examines photoanode modification strategies, including doping methods that improve light absorption. The influence of reactor geometry and electrode arrangement on system performance is critically evaluated, accompanied by a systematic comparison of different doping methods for fabricating photoanodes and the determination of optimum operating conditions to examine electrode performance. Finally, key challenges and promising research directions have been identified that could facilitate the broader application of PEF technology in industrial wastewater treatment.

2- Hybrid Fenton-based processes

2.1. Electro-Fenton processes

EF is a combined electrochemical and Fenton process in which hazardous reagents are detoxified without their handling and addition, and it consumes a low amount of energy with a short process lifetime [45]. This technique could potentially be used to treat wastewater, including industrial and groundwater [46]. In the process of anodic oxidation, H_2O_2 is continuously generated in situ at a suitable cathode through the two-electron reduction of dissolved oxygen as shown in Eq. 2. The pollutants undergo mineralization through either direct electron transfer processes or the action of radical species, specifically hydroxyl radicals, which are produced on the electrode surface, as demonstrated in Eq. 3 [47].

$$O_2 + 2H + 2e^- \rightarrow H_2O_2 \tag{2}$$

$$H_2O_2 \rightarrow {}^{\bullet}OH + H^+ + e^- \tag{3}$$

The free hydroxyl radical is a potent oxidizing agent that can react with organic pollutants in wastewater to form dehydrogenated compounds [48]. Anodic oxidation is typically carried out at the anode in electrochemical cells. In this process, a polluted solution is treated using an anode made of inert materials, commonly composed of BDD and Pt, which are electrodeposited with nanoparticles such as TiO_2, PbO_2, and SnO_2. Under these circumstances, most aromatic solutions exhibit limited mineralization because they produce carboxylic acids that are hard to oxidize [33, 49].

The EF method involves the destruction of pollutants through the combined action of Fenton's reagent in the bulk solution and anodic oxidation at the anode surface. The EF process can be divided into four categories based on the addition or formation of Fenton reagents: cathode EF process (EF-H_2O_2), sacrificial anode EF process (EF-Feox), Fe^{2+} cycling EF process (EF-Fere), and the combined cathode and Fe^{2+} cycling EF process (EF-H_2O_2-Fere). In the EF-H_2O_2 process, externally added Fe^{2+} and in-situ generated H_2O_2 through electrochemical O_2 reduction on the cathode can eliminate the handling, transportation, and storage costs and risks associated with H_2O_2. The EF-Feox process involves externally added H_2O_2 while electro-generating Fe^{2+} using a sacrificial anode. However, this method has drawbacks like high anode consumption and significant iron sludge production. Regarding the EF-Fere process, both H_2O_2 and Fe^{2+} are added externally; however, Fe^{3+} from the Fenton reaction is reduced to Fe^{2+} at the cathode, thereby decreasing iron sludge production and the initial Fe^{2+} concentration input. The EF-H_2O_2-Fere process combines the EF-H_2O_2 and EF-Fere processes. Here, in-situ H_2O_2 generation via cathodic O_2 reduction and Fe^{2+} regeneration through Fe^{3+} reduction on the cathode can eliminate the need for external H_2O_2 addition, reduce iron sludge production, and decrease the initial Fe^{2+} concentration input [50]. The mechanism of reactions in the four different EF processes is illustrated in Fig. 1(a-d).

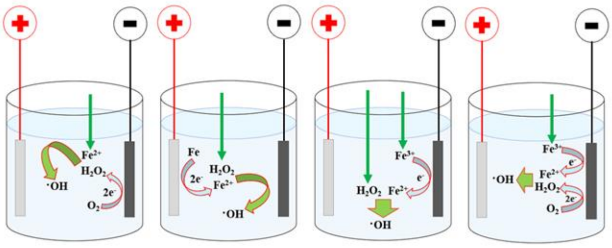

Fig. 1. The reaction mechanisms underlying four different types of EF processes: (a) EF-H_2O_2, (b) EF-Feox, (c) EF-Fere, and (d) EF-H_2O_2-Fere

Abbas and Abbas [51] examined various graphite and carbon fiber electrodes in different electrochemical cells using direct, indirect, and EF processes. The best results were obtained with carbon fiber as a cathode via the EF process, resulting in a 55.59% reduction in phenol after 180 minutes. This finding was attributed to the large surface area of the cathode, which increases hydrogen peroxide production.

Abbas and Abbas [52] prepared and characterized MnO_2-graphite electrodes and examined their efficiency in degrading phenolic compounds from wastewater using the EF process under various operating conditions, including temperature, current density, and ferrous concentration. The maximum COD removal was 88% within a reaction time of six hours.

Kuleyin et al. [53] delved into the efficacy of the EF technology in treating biologically processed textile wastewater using graphite electrodes. The EF process was evaluated in removing color, COD and TOC in batch and continuous modes of operation. Different operation parameters, such as pH, current density, reaction time, and Fenton catalyst concentration, were investigated. In a continuous operational mode, removal rates of 89 % color, 93% COD, and 58% TOC were successfully achieved. The results indicated that using the EF process with graphite anodes and cathodes has the potential to enhance the quality of wastewater for reuse.

Al-Khafaji and Mohammed [54] recommended integrating EC and EF to oxidize organic substances in refinery-produced water, thereby reducing COD to meet statutory limitations. The influence of process variables (current density, pH, and reaction time) on COD removal was investigated by the response surface method. The combination of EC and EF efficiently removes oil-contaminated water, and this process is further enhanced by ultraviolet photolysis. The total COD removal reached a high value of 82.9% within 1 hour.

Salazar and Ureta-Zañartu [55] achieved the complete degradation of the triadimefon conazole fungicide in water at pH 3 using EF and PEF processes. A proposed reaction pathway outlines the oxidation of triadimefon by hydroxyl radicals, explaining the formation of nearly all identified intermediates. The electrochemical setup consisted of a one-compartment cell featuring a glassy carbon mesh cathode and an outer steel mesh anode. Throughout the degradation processes, 4-chlorophenol, hydroquinone, carboxylic acids, and inorganic ions were identified as intermediates, ultimately leading to the complete mineralization of triadimefon to CO_2 and H_2O.

Nayebi and Ayati [56] investigated the effectiveness of removing amoxicillin from hospital wastewater using the electrocoagulation (EF) method with an aluminum anode. Through a methodical approach, the optimal values for various process parameters were identified: the antibiotic initial concentration at 100 $mg.L^{-1}$, reaction time of 90 minutes, initial pH of samples set at neutral, supporting electrolyte concentration of 0.02 M Na_2SO_4, electrode distance of 5.5 cm, and applied current density of 5.5 $mA.cm^{-2}$. Using aluminum anodes significantly improved the process efficiency under neutral pH conditions, achieving a removal rate of approximately 95%. This enhancement could potentially address the constraints faced by traditional EF processes when degrading amoxicillin.

Al-Khafaji and Mohammed [57] suggested using the EF process to degrade organic pollutants in produced water, which is an effluent from an oil refinery. Continuous electrochemical (EF) processes were analyzed using a dimensionally stable anode of Ti-RuO_2/IrO_2 and an activated carbon fiber felt (ACFF) cathode. The effect of operating variables, such as Fenton catalyst concentration, current density, and reaction time, on COD removal efficiency was examined using response surface methodology. Through multiple response optimization for continuous EF experiments, it was revealed that under optimal conditions (Fenton catalyst concentration of 0.306 mM, current density of 156.6 mA, and reaction time of 180 min), the COD removal efficiency reached 73.33% with an electrical energy consumption of 0.901 kWh/kg COD.

Vigil-Castillo et al. [58] conducted a study on degrading the asulam herbicide through the EF process using an undivided electrochemical BDD/carbon felt cell to produce H_2O_2 continuously. A central composite design, in combination with response surface methodology, was employed to determine the optimal operational parameters: a current density of 0.30 A, a Fenton catalyst concentration of 0.3 mM, and a Na_2SO_4 concentration of 0.11 M at pH 3, which ensured complete asulam degradation through electro-Fenton (EF). Aromatic intermediates such as 4-aminobenzenesulfonamide, 4-aminophenol, and 4-benzoquinone were identified, while acetic acid, oxalic acid, and NO_3 ions were characterized as final degradation by-products. This study also conducted a comparison between the EF and PEF using solar irradiation. It was determined that exposure to natural sunlight plays a role in increasing $^{\bullet}OH$ production, and the SPEF process emerges as a viable choice for large-scale water treatment. Table 1 summarizes the materials used for electrodes in EF processes for removing various pollutants in the cited studies.

In summary, the EF processes show promising results in removing various pollutants from different types of wastewaters using diverse electrode materials and configurations. However, its efficiency in removing persistent compounds was relatively low.

2.2. Photoelectro-Fenton processes

PEF processes are advanced oxidation processes that utilize UV light, fluorescent lamps, or sunlight to generate hydroxyl radicals to degrade various pollutants. These processes utilize photocatalysts, such as TiO_2, ZnO, and CuO, which can enhance the efficiency of the degradation reactions. Combining electro-Fenton (EF) and photocatalytic degradation in a photoelectrochemical (PEF) system effectively eliminates pollutants, including organic and inorganic compounds, achieving high degradation efficiencies. The main operating factors that affect the performance of the PEF process are pH, initial concentration of pollutant, current density, and type of catalyst [59, 68-70].

Table 1. Summary of electrode materials in EF processes for the degradation of various pollutants

Pollutant (s)	Electrode		Time, min	Removal Eff., %	Ref.
	Anode	Cathode			
Phenol	Graphite	Carbon fiber	180	55.59%	[51]
Phenol	Graphite	Graphite	180	88.01%	[52]
Textile Wastewater	Graphite	Graphite	30	88%	[53]
Produced Water	Ti-RuO_2/IrO_2	ACFF	60	82.9%	[54]
Pesticides	Steel mesh	Carbon mesh	30	26%	[55]
Amoxicillin	Aluminum	Graphite	90	95%	[56]
Produced Water	Ti-RuO_2/IrO_2	ACFF	180	73.33%	[57]
Erythrosine B dye	BDD	Carbon felt	120	90%	[59]
Pesticides (triclopyr)	IrO2	Carbon-PTFE air-diffusion	300	30%	[60]
Pesticides (triclopyr)	BBD	Carbon-PTFE air-diffusion	270	47%	[60]
Ponceau SS diazo dye	Ti/Pt	Carbon-PTEF air diffusion	360	60%	[61]
Ponceau SS diazo dye	BBD	Carbon-PTEF air diffusion	360	70.6%	[61]
Methyl orange dye	Pt	Fe-Activated carbon	30	96%	[62]
Sulfonamide	Pt	Carbon-felt	480	95%	[63]
Sulfonamide	BDD	Carbon-felt	190	50%	[63]
Naproxen	Pt	Carbon-PTEF air diffusion	240	40%	[64]
Naproxen	BBD	Carbon-PTEF air diffusion	240	46%	[64]
Naproxen	IrO_2	Carbon-PTEF air diffusion	240	49%	[64]
Sulfamethoxazole	RuO_2/Ti	ACF felt	360	63%	[65]
Acetaminophen	Ti/RuO_2/IrO_2	SS	120	98%	[66]
Landfill leachate	BBD	Carbon felt	240	66%	[67]

The PEF process utilizes UVC light with a wavelength ranging from 200 to 280 nm. The primary advantage of this process is the continuous generation of hydrogen peroxide (H_2O_2) through the reduction of oxygen (O_2) on a carbon-based cathode, as illustrated in Eq. 4. The procedure involves the production of hydroxyl radical ($^{\bullet}OH$) by catalytically decomposing H_2O_2 with Fe^{2+}, as shown in Eq. 5, in an acidic medium with a pH of 2-3. Furthermore, the simultaneous cathodic regeneration of Fe^{2+} is performed to avoid the accumulation of iron sludge, as shown in Eq. 6 [71]. In addition, the utilization of UV light in the PEF process accelerates the degradation of contaminants through the implementation of the following mechanisms: (i) photochemical regeneration of Fe^{2+} by photoreduction of Fe^{3+} to generate a larger amount of hydroxyl radicals, as shown in Eq. 7, and ii) photolysis of H_2O_2 molecules to generate $^{\bullet}OH$ as shown in Eq. 8 [59].

$$O_2 + 2H^+ + 2e^- \rightarrow H_2O_2 \tag{4}$$

$$H_2O_2 + Fe^{2+} \rightarrow Fe^{3+} + {}^{\bullet}OH + OH^- \tag{5}$$

$$Fe^{3+} + e^- \rightarrow Fe^{2+} \tag{6}$$

$$Fe^{3+} + H_2O + h\nu \rightarrow Fe^{2+} + {}^{\bullet}OH + H^+ \tag{7}$$

$$H_2O_2 + h\nu \rightarrow 2{}^{\bullet}OH \tag{8}$$

The PEF process facilitates the degradation of recalcitrant carboxylic acid intermediates that often accumulate during Fenton and EF treatments. The photo-decarboxylation pathway contributes significantly to achieving complete mineralization of organic pollutants [72]. When semiconductor photoanodes are employed in PEF systems, additional photocatalytic pathways contribute to pollutant degradation by generating electron-hole pairs and subsequently forming reactive oxygen species, as illustrated in Eqs. 9-12.

$$\text{Photoanode} + h\nu \rightarrow e^- + h^+ \tag{9}$$

$$h^+ + H_2O \rightarrow {}^{\bullet}OH + H^+ \tag{10}$$

$$e^- + O_2 \rightarrow {}^{\bullet}O_2^- \tag{11}$$

$${}^{\bullet}O_2^- + H^+ \rightarrow HO_2^{\bullet} \rightarrow H_2O_2 \rightarrow {}^{\bullet}OH \tag{12}$$

One of the primary limitations of PEF processes is the necessity for suitable lamps to generate artificial UV light, resulting in a potential up to 40% increase in operating costs compared to the Fenton process [73]. Babuponnusami and Muthukumar [74] conducted a comparative study on the performance of advanced oxidation processes, including Fenton, EF, sonoelectro-Fenton, and photoelectron-Fenton, for eliminating phenol. This study observed that the degradation efficiency follows the order PEF < SEF < EF < F. The photoelectron-Fenton process achieved complete degradation of phenol and 64.19% mineralization after 30 minutes. Meanwhile, Fenton and EF required more time for the degradation and mineralization of phenol.

A study by Da Costa Soares et al. [60] addressed the challenge of the Fenton-based process at neutral pH for the mineralization of herbicides, utilizing Fe(II)-EDDS as a catalyst. The first scope was a comparison study to evaluate the performance of an anode made from BDD and IrO_2 in the PEF process for degrading triclopyr. The results showed a clear enhancement in the electrolytic mineralization of pollutants with the BDD anode compared to IrO_2, due to the high yield of hydroxyl radicals. On the contrary, the anode based on IrO_2 is more cost-effective. In addition to the original research objective, the effect of PEF on the degradation profile was investigated in comparison with SPEF. Because the photon intensity of sunlight is higher than that of UV, the photolytic reaction rate is enhanced, producing hydroxyl radicals, which in turn improve the EF process. Studies have demonstrated that SPEF is more effective than PEF under identical operating conditions.

Dos Santos et al. [61] studied and compared the effectiveness of various electrochemical methods, including EC-H_2O_2, EF, PEF, and PF-based processes, for a similar electrolyte of Ponceau SS diazo dye in an acidic sulfate medium, employing Pt-air diffusion and BBD-air diffusion anodes to investigate their performance. The study found that BBD anodes increased degradation and mineralization; however, it recommended using Pt anodes for PEF because they were more cost-effective than BBD anodes. This study demonstrated the potential of using iron-recycled moieties grafted to activated carbon electrodes to remove the need for iron salts in EF reactions, thereby overcoming the inherent requirement for iron salts in EF and PEF processes. The effectiveness of the PEF process was assessed based on the decolorization and oxidation of the dye solution following a defined electrolysis time. Results showed that using Fe/AC material in the PEF process significantly improved color removal and total organic carbon (TOC) reduction, confirming the effectiveness of the Fe/AC electrode in the PEC degradation of pollutants.

Al-Khafaji and Mohammed [57] investigated the improvement of the continuous EF process using UVA irradiation. The study demonstrated that the COD removal efficiency in continuous EF increased to 81.1% and 86.0% when one and two UVA lamps (3 Watts each) were introduced, respectively. The study concludes that EF is an efficient method for degrading produced water and suggests that further improvements can be made by incorporating photo-assisted techniques.

Crispim et al. [67] demonstrated that using more powerful UV light enhanced the effective removal of COD in the PEF process. Specifically, employing the UVC lamp led to a 1.35-fold increase compared to using the UVA lamp in PEF. This suggests that a higher amount of oxidants were produced during the PEF UVC process, enabling various oxidation mechanisms such as the direct breakdown of the generated byproducts through photolysis and the indirect oxidation by oxidants.

It can be concluded that BBD, Pt, or Ti were served as anodes due to their superior oxidant power, allowing them to generate hydroxyl radicals ($^{\bullet}OH$) directly, with high chemical stability under harsh reaction media and less significant deterioration, and high oxygen over potential which favors the generation of hydroxyl radicals. In the same context, carbon-based cathodes were selected due to their effective production of hydrogen peroxide, which facilitates two-electron oxygen reduction. They also feature a high surface area that increases the reaction site for H_2O_2 generation, a cost-effective, porous structure that promotes efficient oxygen diffusion, good electrical conductivity while remaining stable in the presence of H_2O_2 and generated radicals.

There are several ways to enhance the photoactivity of the electrode surface, thereby increasing the active area for the reaction. These methods mainly include chemical reduction of metal salts and electrical deposition of the anode or cathode electrodes [77]. Electrochemical procedures involve the deposition of various materials. Some examples of these deposited materials include:

1- Coating surfaces with precious metals such as platinum and ruthenium using the galvanic reduction method of salts of those metals, such as titanium nanotubes or meshes [78].
2- Several metals, such as nickel, platinum, tin, and copper alloys, are used in various ways, including immersion, electroless, and cathodic deposition [79].
3- Metal oxides, such as lead dioxide and manganese dioxide, are produced by electrolytic deposition on the anode electrode [80].
4- Improve electrodes by making a composite of different materials, such as metal, ceramic, and polymer coating, using anodic electrodeposition.

Based on a bibliometric study conducted on the Scopus database, the number of scientific studies dedicated to PEF increased by almost 300% between 2010 and 2025, indicating that the scientific community is recognizing its potential for application in wastewater treatment. This promotion of research interest has led to significant progress in PEF technology and equipment, including electrode materials, reactor types, and operating conditions. Table 2 summarizes the maximum wavelength of UV for degrading different pollutants and types of electrodes in PEF processes.

3- Material and configuration of electrodes

Electrochemical (EC) and photoelectrochemical (PEC) reactors have garnered significant attention as promising techniques for wastewater treatment due to their eco-friendly and operational flexibility. The performance of these reactors is highly dependent on the reactor arrangement, and both divided and undivided cells are often used; divided cells avoid the undesired side reactions but lead to increasing electrical resistance, whereas undivided cells provide a simple design and reduce energy cost [34]. The material of the electrodes is vital in terms of their performance, durability, and dimensionally stable anode to be efficient in the degradation of pollutants [81]. In photoelectrochemical technologies, which combine photocatalysis and electrochemical reactions, the source of light is of extreme importance, where UVA (315 to 400 nm wavelength) has cheaper energy and can efficiently activate the widely types of photocatalyst, whereas UVC (100 to 280 nm wavelength) has higher energy and promotes direct photolysis of resistant compounds and intensifies disinfection, although having higher application costs [82]. The synergetic effect of electrochemical processes and photocatalysis in these hybrid reactors has been proven to improve treatment efficiency due to free radical formation and electron-hole separation [83, 84].

Table 2. Summary of operating conditions for different pollutants eliminated using the PEF process

Pollutant	Anode / Cathode	λ_{max} UV (nm)	UV Power (W)	UV Position	Time, min	Removal Eff., %	Ref.
Asulam herbicide	BDD / Carbon felt	360	13	External	180	98%	[58]
Erythrosine B dye	BDD / Carbon felt	360	100	External	90	95%	[59]
triclopyr	IrO_2 / Carbon felt	365	6	External	270	٤٤%	[60]
triclopyr	BBD / Carbon felt	365	6	External	180	66%	[60]
Ponceau SS diazo dye	Pt / Carbon-PTEF air diffusion	360	160	Internal	360	93.4%	[61]
Ponceau SS diazo dye	BBD / Carbon-PTEF air diffusion	360	160	Internal	360	97.6%	[61]
Methyl orange dye	Pt / Fe-Activated carbon	365	75	Internal	30	98%	[62]
Naproxen	Pt / Carbon-PTEF air diffusion	360	160	Internal	120	80%	[64]
Naproxen	BBD / Carbon-PTEF air diffusion	360	160	Internal	120	83%	[64]
Naproxen	IrO_2 / Carbon-PTEF air diffusion	360	160	Internal	120	78%	[64]
Sulfamethoxazole	RuO_2-Ti / ACF felt	365	100	External	360	80%	[65]
Acetaminophen	Ti-RuO_2-IrO_2 / SS	360	48	External	120	97%	[66]
Landfill leachate	BBD / Carbon felt	360	6	External	240	68%	[67]
Landfill leachate	BBD / Carbon felt	254	6	External	240	89%	[67]
Herbicide	Pt /Carbon-air diffusion	300	160	External	120	75%	[75]
Acid Blue 92	BBD / CNTs–PTFE	254	15	External	45	85%	[76]

In this section of the study, we will review innovative electrochemical and photoelectrochemical reactors used for wastewater treatment. This review will address the electrode materials, the arrangement of the electrodes within the reactors, and the types of light irradiation used in the photoelectrochemical reactors.

McQuillan et al. [46] evaluated the capability of inexpensive and readily available graphite electrodes to enhance the path of the EF process. A novel approach of the EF reactor was characterized in the electrolysis system using five graphite rods (diameter of 6.3 mm) arranged vertically in a circular configuration as a cathodic region, with a single carbon rod (diameter of 8 mm) inserted in the reactor as an anodic region. The anode and cathode distance was set at a fixed distance of 10 mm in all experiments. The EF cell layout used in this study is shown in Fig. 2a.

Montenegro-Ayo et al. [85] proposed a new pre-pilot scale reactor to degrade the antibiotic ciprofloxacin in a batch recirculation loop via electrochemical oxidation. The proposed pre-pilot reactor features a circular plate of BDD (10 cm diameter) serving as the reactor's base, in the form of an anode, along with a concave disk of stainless steel (5.5 cm diameter) used as a cathode, positioned 2 cm below the anode. Fig. 2b shows the proposed configuration of a pre-pilot reactor. A mathematical model was conducted using COMSOL Multiphysics software to assess the performance of the proposed reactor.

Lei et al. [86] developed an eccentric column-shaped electrochemical reactor. The reactor consists of the tubular cylindrical cathode (stainless steel) and the Pt-coated Ti anode (economic and high surface area) for precipitation. For uniform current distribution, the cathode (cylindrical) was attached vertically to the inner side of the reactor's wall, and the anode at the center of the reactor, as illustrated in Fig. 2c. In addition, it is possible to automate the buildup of deposits without separating the reactor. First, a study was conducted to verify the viability of this new layout. Furthermore, the formic acid decomposition was evaluated in a continuous flow configuration. Finally, the long-term performance and scalability of the system were assessed.

Abbas and Abbas [52] constructed an undivided electrochemical cell containing a graphite rod with dimensions of (1.5 cm diameter and 6 cm long) which worked as an anode, while the cathode was a hollow-cylindrical graphite with dimensions of (8 cm inner diameter, 10 cm outer diameter, and length 15 cm) as shown in Fig. 2d. This study was concerned with modifying graphite electrodes by electroplating with a phase of γ-MnO_2.

Li et al. [87] discovered a novel type of electrode generated by EF using aeration graphite felt electrodes to remove organic pollutants, which enhanced both the production of H_2O_2 and the cyclic utilization of Fe^{3+}/Fe^{2+} ions. Moreover, the H_2O_2 generation achieved in this method was high (152-169 mg.L^{-1}) at a wide working pH (3-10). The new cell consisted of a piece of graphite with dimensions of 3×4×1.7 cm³ as the active dimension, aerated by inserting eleven fiber tubes that functioned as both cathode and anode, with an active dimension of 3×4 cm², used as a Ti/IrO_2/RuO_2 mesh. The oxygen transfer to the GF fiber was significantly improved due to aeration into the graphite felt electrode, resulting in the formation of H_2O_2. The aeration of the electrode also promoted the rapid mass transfer of ions from the bulk solution to the graphite surface through a turbulent electrolyte flow at the interface and a deep penetration of the electrolyte into the graphite felt. Finally, it enhances the degraded performance.

Liang et al. [88] prepared a novel (VO-EF) system consisting of a VO-based cathode and anode by electrodepositing. Different vanadium oxides on carbon paper (CP) were simultaneously used in an ensemble system for the degradation of levofloxacin under neutral pH conditions. A unique system consisted of a Vox@CP cathode and a V_3O_7@CP anode, each with dimensions of 2×1 cm². The benefit of the VO-EF system was demonstrated by its low energy consumption and H_2O_2 residual compared with the Ferrum-EF system under neutral pH conditions.

The main challenge faced by PEC reactors is the limited surface area available for coating electrodes with photocatalysts. Most previous studies have demonstrated that UV light outside electrochemical cells can irritate the electrodes coated with semiconductor photocatalysts [89].

Nevertheless, this approach encounters challenges related to the stability of the electrodes, which are caused by the leaching of the coatings and the loss of photon transport due to light reflection by the cell glass [90]. Internal light irradiation is favored and used when water is highly turbid or colored, preventing light from reaching the photoanodes in the wastewater medium to be treated [91].

Dos Santos et al. [61] constructed a pre-pilot flow reactor within a polycarbonate box measuring 24×24×25 cm^3, comprising a 20 cm^2 BDD or Pt-air diffusion anode and a 20 cm^2 carbon/PTEF air-diffusion cathode. The scheme compared the performance of AO, PEF, and SPEF in degrading the dye. The electrode gap was 1.2 cm. For photoreactor assessment, a 160 W UV lamp (360 nm wavelength) was centered in the middle of an annular photoreactor, as shown in Fig. 2e. The photoreactor has the following dimensions (11 cm diameter and 21 cm height). Furthermore, the same scheme was previously used to mineralize the herbicide mecoprop [92].

Montenegro-Ayo et al. [90] innovated an annular photo-electrocatalytic reactor with multiple discs coated with TiO_2 nanotubes for the degradation of acetaminophen. A novel reactor has revealed a way to enhance the photoactive surface area in annular reactors, resulting in a reduction in electric energy compared to photocatalysis alone. This reactor involves eight-donut disk electrodes arranged in a perpendicular shape to 14 W of a UV lamp (λ_{max} = 275 nm) in the center of the reactor contained in a quartz tube, as shown in Fig. 2f. The photo-anode discs had a total diameter of 71 mm with a defined surface area of 32 cm^2 per side. In contrast, the cathode discs were 66 mm in diameter with a defined surface area of 30 cm^2 per side. The electrode configuration provided a uniform current density distribution, contributing to improved light radiation. This photoreactor design addresses the issues in light transport and could offer a new methodology for scaling PEC water treatment. This work proposes the design of a PEC reactor that should be optimized in the future based on enhancing light absorption, as the vertical orientation of the electrodes in the current study may limit light penetration and distribution.

Peralta-Hernández et al. [93] designed and fabricated a batch-recycle reactor to remove direct yellow-52 dye. The novel reactor consists of a cylindrical carbon cloth that serves as the outer cathode, with dimensions of 5.3 cm in diameter and 12 cm in length. A cylindrical Ti mesh electrode, with dimensions of 1 cm in diameter and 12 cm in length, is located within the inner electrochemical cell. The electrochemical cell had an outer diameter of 6.0 cm, which enabled the solution to flow on the exterior of the cathode cloth. The electrochemical experiments were conducted using a membrane with a thickness of 0.36 mm, made from porous polysulfonate, between the two electrodes. The purpose of the membrane was to avoid mixing between the electrodes. For photochemical investigations, a UV mercury lamp with a wavelength of 365 nm was inserted inside the hollow tube of a node electrode on its outer surface. The flow rate of solutions remained constant in the annular reactor through all experiments at 100 ml/min. The treated solution in the reservoir was saturated with an oxygen sparger. Fig. 2g illustrates the proposed batch-recycle reactor.

De OS Santos et al. [94] tested the enhancement of the anode electrode material by electrodepositing mixed metal oxide (MMO) and BBD on the degradation of herbicide using EO, EF, and PEF. The Batch reactor contains (60 cm^2) cylindrical carbon felt, which works as a cathode around the reactor’s wall, and a rectangular anode with a dimension of (4 cm^2) as shown in Fig. 2h. PEF experiments were performed using 9 W of UVC (λ_{max} =254 nm) immersed in the solution. The results of this study demonstrated that modifying the anode with MMO improved TOC removal. The efficiency of the compared processes follows this sequence: PEF > EF > EO. Furthermore, the PEF-MMO process exhibited the lowest energy consumption among the methods studied.

Banuelos et al. [62] developed a novel design of a rotating disk slurry electrode (RoDSE) in a reactor, featuring an anode composed of a platinum spiral wire. The cathode was a Fe/AC rotating disk. The RoDSE method is a successful process for electrodeposition of iron on the AC. Additionally, Fe/AC can be prepared with relatively homogeneous iron oxide impregnated by applying the RoDSE technique, which will benefit the cathodic production of hydrogen peroxide and the electrocatalytic performance for EF and PEF. This work aimed to assess the effects of EF and PEF on the degradation and mineralization of the MO dye as a model effluent. PEF experiments were conducted using a UVA lamp (λ_{max}= 365 nm).

Carbon-based materials are the most common cathode materials used in PEF systems due to their ability to reduce oxygen. Different carbon-based materials, such as graphite, carbon felt, carbon cloth, carbon paper, and carbon-PTFE gas diffusion electrodes (GDEs), have shown a high ability for generating hydrogen peroxide [95]. Carbon felt cathodes (CFCs) offer a high specific surface area, electrical conductivity, and mechanical strength, along with certain advantages. Panizza and Oturan [96] reported that H_2O_2 concentrations of 28-35 mM could be obtained in carbon felt cathodes under optimized conditions (pH 3, 300 mA current density, and an airflow rate of 1 L/min). Although carbon felt electrodes frequently have a mass transfer limitation, their three-dimensional structure can limit the diffusion of oxygen towards the active sites. Carbon-PTFE gas diffusion electrodes have been shown to be better alternatives, offering improved oxygen diffusion properties and consequently higher H_2O_2 generation rates. These electrodes comprise a porous carbon film mixed with polytetrafluoroethylene (PTFE) as a binder, which is typically coated on a metal mesh current collector. A hydrophobic PTFE allows the establishment of a three-phase interface (solid electrode/liquid electrolyte/gaseous oxygen) that allows efficient oxygen reduction [97]. The study of Garcia-Segura et al. [98] reported H_2O_2 production rates between 0.42 and 0.58 mmol/h.cm^2 when carbon-PTFE GDEs were used, which was at least four times larger than that reported using carbon felt electrode under the same conditions (0.10-0.15 mmol/h.cm²).

Internal illumination configurations position light sources within the reactor vessel, in direct contact with the solution or separated by transparent protective barriers. These configurations typically employ submersible light sources such as UV-C lamps, UV-LEDs, or fiber optic light distribution systems [99]. The primary advantage of internal illumination is enhanced light utilization efficiency, with minimized losses due to transmission through reactor walls or reflection at interfaces. Additionally, these configurations typically achieve uniform illumination of the photoreactive surfaces and solution volume. However, internal illumination systems face challenges, including potential fouling of light sources, complicated maintenance requirements, and the need for waterproof or protected light source designs [100]. Innovations in internal illumination of PEF reactors include optical photoanode designs, which distribute light throughout the reactor volume. Mousset and Dionysiou [101] reported that PEF reactors incorporating anodes coated with a TiO_2 photocatalyst achieved approximately 70% higher light utilization efficiency and 55% higher pollutant degradation rates compared to conventional external illumination systems of equivalent light source power.

In conclusion, the choice of anode material has a significant impact on the oxidation power of advanced oxidation processes. The most important characteristics in choosing electrodes were their high electrical conductivity, which minimizes ohmic losses and ensures consistent current distribution. Furthermore, efficient electrocatalysts' chemical and mechanical stability will reduce the overpotential required for the desired reaction. When utilizing solar energy as an illumination source, the vertical alignment of the electrodes could potentially restrict the penetration and even distribution of light to the lower electrodes. Conversely, in the case of UV lamps, the electrodes should maintain a minimal distance from the light source to optimize light penetration onto the electrode surface within PEF cells. Table 3 summarizes electrode materials and configurations used in novel electrochemical cells.

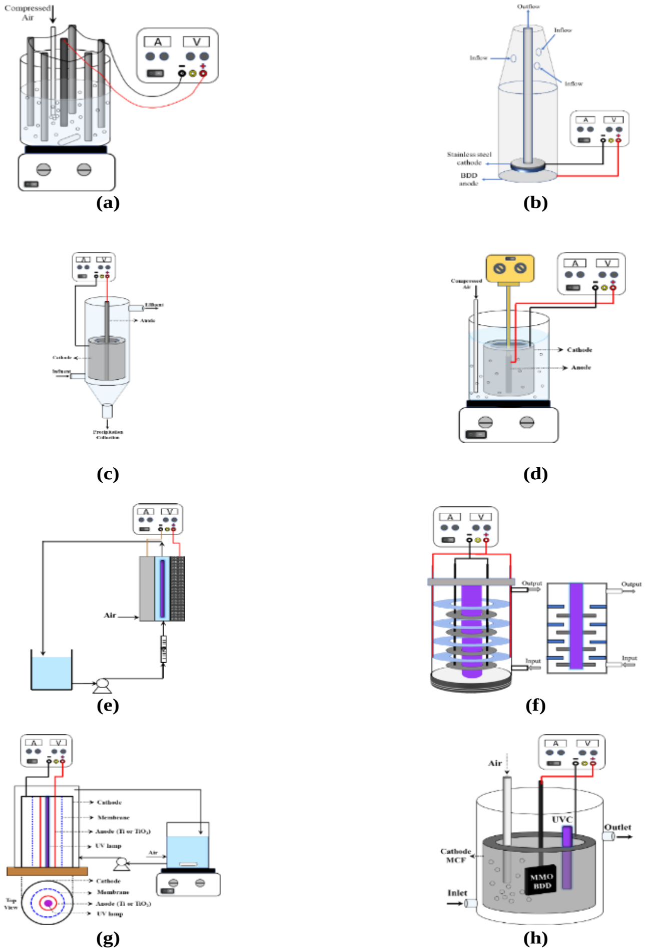

Fig. 2. Novel electrode configurations in electrochemical techniques, (a) McQuillan et al. [46], (b) Montenegro-Ayo et al. [85], (c) Lei et al. [86], (d) Abbas and Abbas [52], (e) Dos Santos et al. [61], (f) Montenegro-Ayo et al. [90], (g) Peralta-Hernández et al. [93], and (h) De OS Santos et al. [94]

Table 3. Summary of novel electrode configurations in electrochemical techniques

Process (s)	**Pollutant (s)**	**Reactor Type**	**Material of electrodes**		**Shape of electrodes**		**Ref.**
			Anode	**Cathode**	**Anode**	**Cathode**	
EF	Naphthalene	Batch	Carbon	graphite	Rod in the center	Five rods around the anode	[46]
ECO	ciprofloxacin	Batch	BDD	Stainless steel	Circular disk	Concave disk	[85]
EC	Phosphorus	Continuous	Pt/Ti	Stainless steel	rod	Tubular	[86]
EF	phenol	Batch	graphite	graphite	rod	Hollow cylinder	[52]
EF	Organic pollutants	Batch	Ti/IrO_2/RuO_2 mesh	Graphite felt	rectangular	rectangular	[87]
EF	levofloxacin	Batch	Carbon paper	Carbon paper	rectangular	rectangular	[88]
EF PEF	Ponceau SS diazo dye	Batch	BDD/Pt	Carbon/PTFE-air diffusion	rectangular	rectangular	[61]
PEC	Acetaminophen	Continuous	TiO_2 nanotube	Ti	donut-shaped discs	donut-shaped discs	[90]
EF PEF	Direct yellow-52	Batch-recycle	Ti mesh semiconductor	Carbon-cloth	cylinder	cylinder	[93]
EF PEF	clopyralid	Batch	MMO/BBD	Carbon felt	rectangular	cylinder	[94]
EF PEF	MO dye	Batch	platinum	Fe/AC	spiral wire	Rotating disk	[62]

PEC reactors play a crucial role in determining their performance for the degradation and mineralization of pollutants from wastewater. Reactor geometry directly influences key operational parameters, including light distribution, mass transfer efficiency, electrode spacing, and fluid flow dynamics, which significantly impact pollutant degradation rates. Literature studies have shown that optimized reactor shapes can enhance light absorption by up to 40% through improved light penetration and reduced shadowing effects [102]. Furthermore, strategic configuration designs that minimize dead zones and promote turbulent flow patterns have demonstrated increased mass transfer coefficients, facilitating faster photocatalyst interactions and reducing treatment times [103]. The arrangement of electrodes within the reactor also affects charge separation efficiency and electron transfer rates, with optimized electrode geometries showing reduced internal resistance and enhanced current densities for oxidation reactions [104]. Recent innovations in reactor design configurations, such as helical and spiral configurations, have improved the reactor performance by 40% compared to conventional rectangular designs. These new configurations maximize the active surface area while maintaining uniform light distribution [105].

4- Types of doping in photoanode synthesis

Developing an efficient method to fabricate photoelectrodes is crucial for advancing wastewater treatment. Photoelectrodes typically consist of semiconductor materials deposited on conductive substrates, with their performance highly dependent on the electronic properties of the semiconductor thin film. Doping semiconductor materials is a fundamental strategy to modify photoanode properties, enhancing charge carrier concentration and improving overall PEC reactor performance [106]. Doping processes are key in determining the physical and chemical properties of photoelectrodes, such as crystallinity, shape, band structure, and carrier transport properties [107]. Consequently, the choice of doping method is crucial for achieving the desired photoelectrode for specific applications. This review examines the primary doping methods employed in photoelectrode preparation, including sol-gel, dip-coating, electrophoretic deposition, and DC sputtering. Knowledge of these doping procedures, their capabilities, and their limitations is crucial for researchers seeking to tailor photoelectrodes to optimal performance and for any potential device application. Doping is a process used to alter the electrical properties of a semiconductor crystal structure by adding controlled amounts of impurity (dopant) atoms into it [108]. Two types of semiconductors exploited for the active layer can be obtained depending on the type of dopant: a) n-type semiconductors (having extra electrons) or b) p-type semiconductors (having missing electrons). The type and concentration of doping elements are well understood to control the charge carrier density, mobility, and recombination rate prerequisites for efficient photoelectrodes [109].

Sol-gel is a colloidal process that produces (open structure) inorganic materials by forming a gel in a solution. For doped photoelectrode fabrication, precursor solutions comprising semiconductor materials and dopant precursors are combined at the molecular level. The sol is hydrolyzed and condensed, forming a gel that is dried and annealed to produce the final doped semiconductor material. This method has several merits, such as a lower temperature process, low cost, adjustable components, and good homogeneity of the dopants [110]. However, the sol-gel suffers from potential cracking during drying, a lack of thickness control, poorer crystallinity compared to other methods, and difficulty obtaining high dopant concentrations [111]. Doped TiO_2, ZnO, Fe_2O_3, and other photoelectrodes can be fabricated using the sol-gel process. For instance, Zhang et al. [112] reported a rapid and cost-effective sol-gel route using polyethylene glycol (PEG) and polyacrylamide (PAM) as co-templates for synthesizing pure and doped mesoporous TiO_2 samples with improved photocatalytic performance.

In the dip-coating process, a substrate is dipped into a precursor solution that contains target semiconductor particles and dopant, after which it is pulled out of the solution at specified moving speeds [113]. During substrate retraction, a thin film solution remains on the surface and then solidifies through evaporation and heat treatment. The submersion process can be repeated several times until the required film thickness is formed. This process has several advantages, including simplicity and low cost, the ability to conformally coat complex features, reasonable control over film thickness from the withdrawal rate, and compatibility with various substrate materials [114]. However, this method still faces some problems, such as a lack of control over microstructure, possible inhomogeneous coating on complex surfaces, its dependence upon the wettability of the substrate, and the need for repeated coatings for thicker films [115]. Xia et al. [116] provided guidance for designing non-metal-doped $BiVO_4$ photoanodes by developing phosphorus-doped $BiVO_4$ (P-$BiVO_4$) photoanodes using dip-coating and thermal treatment. P-$BiVO_4$ demonstrated reduced interface obstruction compared to undoped $BiVO_4$. Additionally, P-$BiVO_4$ exhibited a higher carrier concentration, enhancing its PEC performance.

Electrophoretic deposition (EPD) is the migration of charged particles in suspension under an electric field from one electrode to another, followed by their subsequent deposition as a film [117]. In the preparation of doped photoelectrodes, suspensions of semiconductor particles and their dopant precursors are positioned under the influence of an electric field, which directs the materials to migrate to and deposit on the substrate electrode. This approach offers several benefits, including a rapid deposition rate, well-controlled film thickness, and suitability for complex geometry structures using room-temperature processes [118]. On the other hand, EPD has several limitations, including the requirement for conductive substrates, the need for post-deposition sintering, potential uneven deposition, and a limited particle size range [119]. In this context, self-doped strontium titanate ($SrTiO_3$) with favorable photocatalytic properties was fabricated by applying the electrophoretic deposition (EPD) method to produce $SrTiO_3$ thin films on fluorine-doped tin oxide (FTO) conductive substrates [120].

DC-sputtering is a physical vapor deposition technique where a target material (source) is bombarded with high-energy ions, causing atoms to be ejected and deposited onto a substrate [121]. For the preparation of doped photoelectrodes, either a pre-doped target can be used, or co-sputtering from multiple targets can be performed to achieve the desired doping level. This method has several advantages, such as precise control over film thickness and composition, excellent uniformity across large areas, high reproducibility, good adhesion to substrates, the possibility of graded doping profiles, and compatibility with industrial-scale production [122]. However, several limitations should be considered, including the relatively high equipment cost, the potential for lattice damage due to high-energy deposition, lower deposition rates compared to previous techniques, and the requirement for a vacuum environment. Villamayor et al. [123] synthesized high photocatalytic activity layers by combining a TiO_2 nanostructured coating support with NiO layers using DC-sputtering. The photocatalytic activity of the coatings was evaluated through the degradation of methylene blue under UV light.

4.1. A comparative analysis of doping methods

Different doping methods offer varying levels of control over process parameters. This review examines four doping methods for synthesizing photoanodes: sol-gel, dip-coating, electrophoretic deposition (EPD), and direct current (DC) sputtering. According to the comparative review, it can be concluded that DC-sputtering is a notable method because it allows the film thickness, composition, and microstructure to be controlled relatively precisely by tuning the deposition parameters, including power, pressure, and substrate temperature. This degree of control is essential for the reproducible performance of the photoelectrode.

The effectiveness of doping is contingent upon the ability to control the distribution and concentration of dopants. Both sol-gel and dip coatings offer the advantages of good molecular-level blending, although phase separation may occur during crystallization. As opposed to this, DC sputtering allows for dendritic concentration by the target composition or the co-sputtering rates [124], leading to a larger uniform distribution of dopant atoms. Practical implementations need to be scalable. Sol-gel and dip-coating are standard techniques in laboratory research, and they are generally capable of being scaled up; however, they also have difficulty achieving considerable area uniformity. Although the initial cost of DC sputtering is higher, it is of great practical value, has high scalability, and is of reasonable quality for film, especially for industrial applications [125].

Cost aspects include equipment investments, material usage, energy needs, and processing time. Sol-gel and dip-coating are typically more cost-effective for small production quantities. However, in large-scale production, the DC-sputtering can be more economical [126]. When the equipment cost is not a concern, other deposition systems are not as effective as DC-sputtering equipment due to its high material utilization ratio and formation reproducibility, even though DC-sputtering equipment is more costly compared to the others. Table 4 presents a comparative analysis of the doping methods used to synthesize photoanodes.

Table 4. A comparative analysis of doping methods

Parameter	Sol-Gel	Dip-Coating	EPD	DC-Sputtering
Film uniformity	Moderate	Moderate	Moderate	Excellent
Thickness control	Limited	Moderate	Good	Excellent
Dopant distribution	Good	Moderate	Moderate	Excellent
Dopant concentration control	Moderate	Limited	Limited	Excellent
Crystallinity	Moderate	Moderate	Moderate	Excellent
Scalability	Good	Good	Moderate	Excellent
Equipment cost	Low	Low	Moderate	High
Processing time	Long	Moderate	Short	Moderate
Temperature requirements	High	High	Low	Low
Reproducibility	Moderate	Moderate	Moderate	Excellent

5- Operating parameters of hybrid Fenton processes

The studies on operation parameters that affect the Fenton reaction consist of the pH of wastewater, Fenton catalyst, H_2O_2 concentration, and concentration of organic pollutants, which are extensively focused on in this study to significantly impact the efficiency of Fenton processes in treating refractory organic pollutants. As a result, optimizing the parameters is necessary to achieve the best removal efficiency and minimize economic costs. This section provides an exhaustive literature survey and systematically describes the rules for optimizing the above parameters.

McQuillan et al. [46] assessed the effects of the EF pathway on naphthalene degradation. The influencing parameters on the removal efficiency were evaluated, namely Fe^{2+} concentration (0–2 mM) and current density (0–5 mA). The results reveal the absolute removal of a nearly saturated concentration of naphthalene (20 $mg.L^{-1}$) within less than 3 h of the reaction time under optimum conditions of operating factors (0.06 mM of iron concentration and 5 mA of time).

Banuelos et al. [62] examined the impact of iron concentration on electrodepositing for MO dye degradation and mineralization in the EF process. The higher electrodepositing iron content is beneficial for the production of H_2O_2. A series of experiments was conducted to evaluate the degradation and mineralization of the MO dye, employing three different systems to demonstrate the effectiveness of the proposed EF process with iron electrodeposition on AC compared to other systems. The highest efficiency of color removal and total organic carbon (TOC) removal (98%) was observed for an iron concentration of 1973 mg/kg after 30 minutes.

Montenegro-Ayo et al. [85] conducted experiments in a new pilot reactor to investigate the degradation of the antibiotic pollutant from wastewater in a sulfate medium by varying operating variables, including current density, initial ciprofloxacin concentration, and pH. The operating parameters studied were current density (15-60) $mA.\ cm^{-2}$, initial ciprofloxacin (5-30) $mg.L^{-1}$, and pH (3–10) in the presence of 0.05M Na_2SO_4 as supporting electrolyte. Experimental work on COD and average current efficiency (ACE) is conducted. At optimal operating conditions, the maximum removal of COD and average current efficiency (ACE) were 94% and 14.3%, respectively.

Babuponnusami and Muthukumar [74] investigated the operational parameters (current density, H_2O_2 concentration, Fe^{2+} concentration, distance between anode and cathode, pH, and initial phenol concentration) that affect the electrochemical degradation of phenol in their study. The study findings indicated that the optimum operating conditions regarding phenol degradation and COD removal were obtained at 5 cm electrode distance, for the H_2O_2 concentration of 500 $mg.L^{-1}$, Fe^{2+} dosage of 4 $mg.L^{-1}$, initial pH of 3, and the current density of 12 $mA.cm^{-2}$.

Abbas and Abbas [52] studied the effect of Fe^{2+} concentration (0.05-0.4) mM, temperature (30-60) ºC, current density (2-8) mA, and reaction time (1-6 h) on the phenol degradation. Maximum COD removal was achieved at optimum operating conditions with 6 h reaction time, current density of 8 $mA.cm^{-2}$, and Fe^{2+} concentration of 0.4 mM (88.01%). The maximal SPC was 10.22 kW/kg COD.

Liang et al. [88] developed a novel VO-EF system with a VOx@CP cathode and a V_3O_7@CP anode for the degradation of levofloxacin under neutral pH conditions. Effect of pH, reaction time, and initial concentration of levofloxacin. In 600 min at pH 7.30, the VO-EF system could remove 19.19 mg/L TOC with a low electrical conductivity (EC) of 12.3 J/mg/L TOC. The H_2O_2 production rate in the reaction was calculated using the potassium titanium (IV) oxalate method.

Peralta-Hernández et al. [93] investigated the impact of operational factors, including solution flow rate, reaction time, and Fe^{2+} concentration, on the coupled process of EF and PEF for degrading organic pollutants. At the optimum operating conditions, the study showed that H_2O_2 generation increased by 30% in the PEF process compared to the EF process. Similarly, the TOC increased from 24 to 57% in EF and PEF, respectively.

Table 5 presents a summary of operating factors and responses for different AOPs, and Table 6 summarizes the optimal values of operating conditions. Research studies predominantly demonstrate improved outcomes when operating at a pH near 3. This phenomenon likely results from the breakdown of parasitic hydrogen peroxide into water and oxygen as pH levels increase. Additionally, some studies suggest that an acidic medium promotes iron leaching, potentially explaining the enhanced performance observed around pH 3 due to a higher presence of homogeneous reactions. Depending on operating conditions, the Fenton catalyst ($Fe_2SO_4{\cdot}7H_2O$) concentration in wastewater solution typically ranges from 0.3 to 0.6 mM. The supporting electrolyte (Na_2SO_4) in the test solution should be supplied at a concentration of 0.05 M to provide the desired conductivity of 10,000 μS·cm⁻¹ [127].

Table 5. Summary of operating parameters and responses for different processes

Process	Pollutant	Operating Conditions	Response	Ref.
EF	naphthalene	Iron concentration, current density	Removal eff.	[46]
EF	Phenol	Temperature, current density, Fe^{2+} concentration, reaction time	COD CE SPC	[52]
EF PEF	MO dye	Reaction time, Iron depositing concentration	Color removal TOC	[62]
F, EF, PEF, SEF	Phenol	Initial Conc., H_2O_2 Conc., Fe^{2+} Conc., Current density, pH, Distance between electrodes	COD EC CE	[74]
ECO	ciprofloxacin	Current density, Initial concentration of ciprofloxacin, and pH	CE ACE	[85]
EF	levofloxacin	pH, reaction time, initial concentration	TOC EC	[88]
EF PEF	Direct yellow-52 dye	Time, flow rate, concentration of Fe^{2+}	H_2O_2 generation TOC	[93]

Table 6. Summary of optimal operating conditions and responses

Pollutant	Optimum conditions	Responses	Ref.
Naphthalene	0.06 mM iron concentration, 5 mA current density	Removal Eff. 100%	[46]
Phenol	8mA/cm^2 current density, 0.4 mM Fe^{2+}, 60ºC temperature, 6 h reaction time	COD 88.01% CE 46.1% SPC 10.22 kW/kg COD	[52]
MO dye	30 min time, 1973 mg/kg iron concentration	Color 98% TOC 98%	[62]
Phenol	pH 3, 4 mg.L^{-1} Fe^{2+}, 500 mg.L^{-1} H_2O_2, 12 mA/cm^2 current density, 5 cm distance	COD_{PEF} 64.19% COD_{SEF} 67.93% EC 18.53 kW/kg COD CE 75.46%	[74]
Ciprofloxacin	60 mA/cm^2 current density, 5 mg.L^{-1} initial ciprofloxacin and 10 pH	CE 94% AEC 14.3%	[85]
Levofloxacin	pH 7.3, 600 min time, 30 mg.L^{-1} initial concentration	TOC 80% EC 12.3 J.mg/l	[88]
Organic pollutants	25 min time, 100 ml.min^{-1} flow rate, 0.5 mM Fe^{2+}	$H_2O_{2\ EF}$ 70 ppm $H_2O_{2\ PEF}$ 100 ppm TOC_{EF} 24% TOC_{PEF} 57%	[93]

6- Recommendations for further work

- Using multi-electrode stacked reactors, constructed with materials resistant to harsh reaction conditions, reduces energy consumption and improves pollutant removal efficiency. However, in the case of solar energy as a light source, the vertical orientation of the electrodes may have limited light penetration and distribution at the lower electrodes. Cornejo et al. [128] recommended designing multicell stacks that enable the assembly of porous or plate BDD electrodes to enhance energy consumption and current efficiency.
- The electrode shape plays a crucial role in enhancing light irradiation on photoanode surfaces in PEF reactors. Walsh et al. [77] emphasized that surface decoration and modification of electrode supports can improve the active area and positively impact electrochemical cell performance.
- Consider the geometry and suitability of laboratory reactors for industrial applications in treating wastewater from industrial effluents. Peralta-Hernández et al. [93] proposed that the concentration of H_2O_2 depends on cell geometry and flow rate in the proposed reactor.
- Experiments on various pollutants over extended periods are essential to demonstrate the reactor's stability, efficiency, and effectiveness in treating industrial wastewater. Montenegro-Ayo et al. [90] suggested that investigating the scalability of the annular reactor design and its application in larger-scale water treatment systems would be valuable for practical implementation. In addition, they recommended conducting long-term operation studies to assess the stability and durability of the photo electrocatalytic reactor under continuous operation, and varying pollutant concentrations would provide insights into its real-world applicability.

7- Conclusion

The PEF process is highly efficient at degrading resistant pollutants in wastewater systems. The investigations detailed in this assessment show that the main deductions derived from this analysis are as follows:

- The fabrication of photoelectrodes with heterojunction composites by doping nanostructured semiconductor materials enhances the efficiency of

PEF reactors in degrading pollutants, especially in acidic media.

- Using photoanodes in a PEF cell can directly produce •OH radicals and oxidize pollutants. Similarly, using a carbon-based cathode can efficiently generate H_2O_2, which participates in the Fenton reaction with Fe^{2+} to produce additional •OH radicals. UV irradiation enhances the process by photo-reducing Fe^{3+} back to Fe^{2+} and photolyzing H_2O_2. This electrode combination effectively creates a synergistic system for PEF reactions.
- The vertical arrangement of electrodes in the PEF cells can limit the amount of solar radiation reaching and being dispersed across the lower electrodes. On the other hand, using a UV lamp will provide excellent light penetration into the surface of the electrodes in these cells.
- The electrode surfaces' smoothness, mirroring, and reflectivity significantly influence light acquisition capacity, directly impacting removal efficiency. Consequently, the most effective coating method for removing pollutants from wastewater.
- The performance of the PEF reactor in treating wastewater is significantly enhanced by using a UVC lamp instead of a UVA lamp. This improvement results in the production of a greater amount of oxidants during the PEF-UVC process.
- Internal illumination configurations of light sources within reactor vessels achieve uniform illumination of photoreactive surfaces. Studies have demonstrated enhanced removal efficiency with internal illumination compared to external systems of equivalent light source power.

A comparative analysis of electrode materials reveals that photoanodes fabricated by DC sputtering outperform those prepared by conventional methods in terms of degradation efficiency, light absorption, operational stability, and applicability for industrial wastewater treatment.

References

[1] I. H. Dakhil, "Adsorption of Lead from Industrial Effluents using Rice Husk," *International Journal of Engineering and Management Research (IJEMR),* vol. 5, no. 1, pp. 109-116, 2015.

[2] S. Garcia-Segura, J. D. Ocon, and M. N. Chong, "Electrochemical oxidation remediation of real wastewater effluents : A review," *Process Safety and Environmental Protection,* vol. 113, pp. 48-67, 2018. https://doi.org/10.1016/j.psep.2017.09.014

[3] I. H. Dakhil, "Effect of Adding Zinc Oxide on Waste Rubber Tire Powder for Increasing Adsorption of Cadmium (II) from Wastewater," *The Iraqi Journal For Mechanical And Material Engineering,* 2015.

[4] O. M. Rodriguez-Narvaez, J. M. Peralta-Hernandez, A. Goonetilleke, and E. R. Bandala, "Treatment technologies for emerging contaminants in water: A review," *Chemical Engineering Journal,* vol. 323, pp. 361-380, 2017. https://doi.org/10.1016/j.cej.2017.04.106

[5] I. H. Dakhil, G. F. Naser, and A. H. Ali, "Assessment of Modified Rice Husks for Removal of Aniline in Batch Adsorption Process: Optimization and Isotherm Study," *Journal of Ecological Engineering,* vol. 22, no. 7, 2021. https://doi.org/10.12911/22998993/138900

[6] S. K. Barno, H. J. Mohamed, S. M. Saeed, M. J. Al-Ani, and A. S. Abbas, "Prepared 13X zeolite as a promising adsorbent for the removal of brilliant blue dye from wastewater," *Iraqi Journal of Chemical and Petroleum Engineering* vol. 22, no. 2, pp. 1-6, 2021. https://doi.org/10.31699/IJCPE.2021.2.1

[7] F. E. Titchou, H. Zazou, H. Afanga, J. El Gaayda, R. A. Akbour, and M. Hamdani, "Removal of persistent organic pollutants (POPs) from water and wastewater by adsorption and electrocoagulation process," *Groundwater for Sustainable Development,* vol. 13, p. 100575, 2021. https://doi.org/10.1016/j.gsd.2021.100575

[8] M. Banaś and B. Hilger, "Proposal for New Method for Calculating Sedimentation Process Efficiency in Water Treatment Plants," (in eng), *Materials (Basel),* vol. 17, no. 13, 2024. https://doi.org/10.3390/ma17133285

[9] S. K. Al-Amshawee, M. Y. Yunus, and I. H. Dakhil, "Ion exchange membrane electrodialysis for water and wastewater processing: application of ladder-type membrane spacers to impact solution concentration and flow dynamics," *Environmental Science and Pollution Research,* pp. 1-22, 2023. https://doi.org/10.1007/s11356-023-27940-z

[10] S. K. A. Al-Amshawee, M. Y. Bin Mohd Yunus, and I. Habib Dakhil, "Multilayered membrane spacer: does it enhance solution mixing?," *Journal of Chemical Technology & Biotechnology,* vol. 98, no. 11, pp. 2627-2638, 2023. https://doi.org/10.1002/jctb.7344

[11] L. Mishra, K. K. Paul, and S. Jena, "Coke wastewater treatment methods: mini review," *Journal of the Indian Chemical Society,* vol. 98, no. 10, p. 100133, 2021. https://doi.org/10.1016/j.jics.2021.100133

[12] I. H. Dakhil, "Adsorption of Chromium (VI) from Aqueous Solutions using Low Cost Adsorbent: Equilibrium and Regeneration Studies," *Journal of Engineering,* vol. 19, no. 11, pp. 1395-1407, 2013. https://doi.org/10.31026/j.eng.2013.11.04

[13] I. H. Dakhil, G. F. Naser, and A. H. Ali, "Response Surface Modeling of Arsenic Adsorption by Modified Spent Tea Leaves," in *IOP Conference Series: Materials Science and Engineering*, 2021, vol. 1090, no. 1, p. 012129: IOP Publishing. https://doi.org/10.1088/1757-899X/1090/1/012129

[14] S. Roy, A. Garg, S. Garg, and T. A. Tran, *Advanced industrial wastewater treatment and reclamation of water*. Springer, 2022. https://doi.org/10.1007/978-3-030-83811-9

[15] B. Wang, Z. Song, and L. Sun, "A review: Comparison of multi-air-pollutant removal by advanced oxidation processes–Industrial implementation for catalytic oxidation processes," *Chemical Engineering Journal*, vol. 409, p. 128136, 2021. https://doi.org/10.1016/j.cej.2020.128136

[16] I. H. Dakhil, "Removal of Kerosene from Wastewater Using Locally Sawdust," in *Proceeding of 1st International Conference of Southern Technical University/Iraq*, 2016, vol. 16, p. 17.

[17] J. L. Wang and L. J. and Xu, "Advanced Oxidation Processes for Wastewater Treatment: Formation of Hydroxyl Radical and Application," *Critical Reviews in Environmental Science and Technology*, vol. 42, no. 3, pp. 251-325, 2012. https://doi.org/10.1080/10643389.2010.507698

[18] M. A. Oturan and J. J. Aaron, "Advanced oxidation processes in water/wastewater treatment: principles and applications. A review," *Critical reviews in environmental science technology*, vol. 44, no. 23, pp. 2577-2641, 2014. https://doi.org/10.1080/10643389.2013.829765

[19] Y. Liu and J. Wang, "Multivalent metal catalysts in Fenton/Fenton-like oxidation system: A critical review," *Chemical Engineering Journal*, vol. 466, p. 143147, 2023. https://doi.org/10.1016/j.cej.2023.143147

[20] S. Lim, J. L. Shi, U. von Gunten, and D. L. McCurry, "Ozonation of organic compounds in water and wastewater: A critical review," *Water Research*, vol. 213, p. 118053, 2022. https://doi.org/10.1016/j.watres.2022.118053

[21] R. Jassim and A. Abbas, “Congo red dye removal from aqueous solutions by photocatalytic redox reactions: Degradation kinetics and simulation using dispersion model”, *Environmental Research and Technology*, vol. 8, no. 3, pp. 672–681, 2025. https://doi.org/10.35208/ert.1527903

[22] A. H. Ali, Dakhil, I. H., "Photocatalytic decolorization of Methyl Red dye under solar light," *Jornal of kerbala university*, vol. 10, no. 3, 2012.

[23] C. Feng, N. Sugiura, S. Shimada, and T. Maekawa, "Development of a high performance electrochemical wastewater treatment system," *Journal of Hazardous Materials*, vol. 103, no. 1, pp. 65-78, 2003. https://doi.org/10.1016/S0304-3894(03)00222-X

[24] M. Z. Akbari, Y. Xu, Z. Lu, and L. Peng, "Review of antibiotics treatment by advance oxidation processes," *Environmental Advances*, vol. 5, p. 100111, 2021. https://doi.org/10.1016/j.envadv.2021.100111

[25] S. K. Kamal and A. S. Abbas, "Decrease in the organic content of refinery wastewater by photocatalytic Fenton oxidation using iron-doped zeolite: Catalyst preparation, characterization, and performance," *Chemical Engineering Processing-Process Intensification*, vol. 193, p. 109549, 2023. https://doi.org/10.1016/j.cep.2023.109549

[26] I. A. Taher, Dakhil, I.H., Kubba, Ziyad, Ali, Ahmed Hassan, "Degradation High Concentration of Eosin Yellowish Dye in Heterogeneous Catalyst Solution," *Journal of Global Pharma Technology*, vol. 10, no. 11, pp. 704-709, 2018.

[27] R. N. Abbas and A. S. Abbas, "Kinetics and energetic parameters study of phenol removal from aqueous solution by electro-fenton advanced oxidation using modified electrodes with PbO2 and graphene," *Iraqi Journal of Chemical and Petroleum Engineering*, vol. 23, no. 2, pp. 1-8, 2022. https://doi.org/10.31699/IJCPE.2022.2.1

[28] M. Kurian, "Advanced oxidation processes and nanomaterials-a review," *Cleaner Engineering and Technology*, vol. 2, p. 100090, 2021. https://doi.org/10.1016/j.clet.2021.100090

[29] S. K. Kamal and A. S. Abbas, "Fenton oxidation reaction for removing organic contaminants in synesthetic refinery wastewater using heterogeneous Fe-Zeolite: An experimental study, optimization, and simulation," *Case Studies in Chemical Environmental Engineering*, vol. 8, p. 100458, 2023. https://doi.org/10.1016/j.cscee.2023.100458

[30] H. J. H. Fenton, "Oxidation of tartaric acid in presence of iron," *Journal of the Chemical Society, Transactions*, vol. 65, pp. 899-910, 1894. https://doi.org/10.1039/CT8946500899

[31] J. J. Pignatello, E. Oliveros, and A. MacKay, "Advanced oxidation processes for organic contaminant destruction based on the Fenton reaction and related chemistry," *Critical reviews in environmental science technology*, vol. 36, no. 1, pp. 1-84, 2006. https://doi.org/10.1080/10643380500326564

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

[33] A. Babuponnusami and K. Muthukumar, "A review on Fenton and improvements to the Fenton process for wastewater treatment," *Journal of Environmental Chemical Engineering*, vol. 2, no. 1, pp. 557-572, 2014. https://doi.org/10.1016/j.jece.2013.10.011

[34] C. A. Martínez-Huitle and E. Brillas, "Decontamination of wastewaters containing synthetic organic dyes by electrochemical methods: A general review," *Applied Catalysis B: Environmental*, vol. 87, no. 3, pp. 105-145, 2009. https://doi.org/10.1016/j.apcatb.2008.09.017

[35] F. C. Moreira, R. A. R. Boaventura, E. Brillas, and V. J. P. Vilar, "Electrochemical advanced oxidation processes: A review on their application to synthetic and real wastewaters," *Applied Catalysis B: Environmental*, vol. 202, pp. 217-261, 2017. https://doi.org/10.1016/j.apcatb.2016.08.037

[36] W. P. Ting, M. C. Lu, and Y. H. Huang, "The reactor design and comparison of Fenton, electro-Fenton and photoelectro-Fenton processes for mineralization of benzene sulfonic acid (BSA)," *Journal of hazardous materials*, vol. 156, no. 1-3, pp. 421-427, 2008. https://doi.org/10.1016/j.jhazmat.2007.12.031

[37] S. Malato, P. Fernández-Ibáñez, M. I. Maldonado, J. Blanco, and W. Gernjak, "Decontamination and disinfection of water by solar photocatalysis: recent overview and trends," *Catalysis today*, vol. 147, no. 1, pp. 1-59, 2009. https://doi.org/10.1016/j.cattod.2009.06.018

[38] O. M. Cornejo, I. Sirés, and J. L. Nava, "Characterization of a flow-through electrochemical reactor for the degradation of ciprofloxacin by photoelectro-Fenton without external oxygen supply," *Chemical Engineering Journal*, vol. 455, p. 140603, 2023. https://doi.org/10.1016/j.cej.2022.140603

[39] A. Ledezma Estrada, Y.-Y. Li, and A. Wang, "Biodegradability enhancement of wastewater containing cefalexin by means of the electro-Fenton oxidation process," *Journal of Hazardous Materials*, vol. 227-228, pp. 41-48, 2012. https://doi.org/10.1016/j.jhazmat.2012.04.079

[40] H. Olvera-Vargas, C. Trellu, P. V. Nidheesh, E. Mousset, S. O. Ganiyu, C. A. Martínez-Huitle, M. Zhou, and M. A. Oturan, "Challenges and opportunities for large-scale applications of the electro-Fenton process," *Water Research*, vol. 266, p. 122430, 2024. https://doi.org/10.1016/j.watres.2024.122430

[41] C. A. Martínez-Huitle and M. Panizza, "Electrochemical oxidation of organic pollutants for wastewater treatment," *Current Opinion in Electrochemistry*, vol. 11, pp. 62-71, 2018. https://doi.org/10.1016/j.coelec.2018.07.010

[42] F. Yu, M. Zhou, and X. Yu, "Cost-effective electro-Fenton using modified graphite felt that dramatically enhanced on H2O2 electro-generation without external aeration," *Electrochimica Acta*, vol. 163, pp. 182-189, 2015. https://doi.org/10.1016/j.electacta.2015.02.166

[43] S. Garcia-Segura, M. Lanzarini-Lopes, K. Hristovski, and P. Westerhoff, "Electrocatalytic reduction of nitrate: Fundamentals to full-scale water treatment applications," *Applied Catalysis B: Environmental*, vol. 236, pp. 546-568, 2018. https://doi.org/10.1016/j.apcatb.2018.05.041

[44] M. Coha, G. Farinelli, A. Tiraferri, M. Minella, and D. Vione, "Advanced oxidation processes in the removal of organic substances from produced water: Potential, configurations, and research needs," *Chemical Engineering Journal*, vol. 414, p. 128668, 2021. https://doi.org/10.1016/j.cej.2021.128668

[45] G. F. Naser, I. H. Dakhil, and A. A. Hasan, "Evaluation of electro-fenton process for removal of amoxicillin from simulated wastewater," *Global NEST Journal*, vol. 26, pp. 1-6, 2024. https://doi.org/10.30955/gnj.006075

[46] R. V. McQuillan, G. W. Stevens, and K. A. Mumford, "Assessment of the electro-Fenton pathway for the removal of naphthalene from contaminated waters in remote regions," *Science of the Total Environment*, vol. 762, p. 143155, 2021. https://doi.org/10.1016/j.scitotenv.2020.143155

[47] R. Abbas and A. S. Abbas, "PbO2/graphite and graphene/carbon fiber as an electrochemical cell for oxidation of organic contaminants in refinery wastewater by electrofenton process; electrodes preparation, characterization and performance," *Environmental Research and Technology*, vol. 7, no. 2, pp. 175-185, 2024. https://doi.org/10.35208/ert.1378232

[48] H. H. Thwaini, R. H. Salman, and W. S. Abdul-Majeed, "Performance of Electro-Fenton Process for Phenol Degradation Using Nickel Foam as a Cathode," *Iraqi Journal of Chemical Petroleum Engineering*, vol. 24, no. 3, pp. 13-25, 2023. https://doi.org/10.31699/IJCPE.2023.3.2

[49] Z. I. Abbas and A. S. Abbas, "Optimization of the electro-Fenton process for cod reduction from refinery wastewater," *Environmental Engineering Management Journal*, vol. 19, no. 11, 2020.

[50] Z. U. H. Khan, N. S. Gul, S. Sabahat, J. Sun, K. Tahir, N. S. Shah, N. Muhammad, A. Rahim, M. Imran, J. Iqbal, T. M. Khan, S. Khasim, U. Farooq, and J. Wu, "Removal of organic pollutants through hydroxyl radical-based advanced oxidation processes," *Ecotoxicology and Environmental Safety*, vol. 267, p. 115564, 2023. https://doi.org/10.1016/j.ecoenv.2023.115564

[51] A. S. Abbas and R. N. Abbas, "Phenol deterioration in refinery wastewater through advanced electrochemical oxidation reactions using different carbon fiber and graphite electrodes configurations," *Egyptian Journal of Chemistry*, vol. 65, no. 13, 2022. https://doi.org/10.21608/EJCHEM.2022.123342.5510

[52] Z. I. Abbas and A. S. Abbas, "Oxidative degradation of phenolic wastewater by electro-fenton process using MnO2-graphite electrode," *Journal of Environmental Chemical Engineering*, vol. 7, no. 3, p. 103108, 2019. https://doi.org/10.1016/j.jece.2019.103108

[53] A. Kuleyin, A. Gök, and F. Akbal, "Treatment of textile industry wastewater by electro-Fenton process using graphite electrodes in batch and continuous mode," *Journal of Environmental Chemical Engineering*, vol. 9, no. 1, p. 104782, 2021. https://doi.org/10.1016/j.jece.2020.104782

[54] R. Q. Al-Khafaji and A. H. Mohammed, "Performance of Combined Electrocoagulation-Advanced Electrochemical Oxidation Used for Oil Field Produced Water Treatment," *Journal of Petroleum Research & Studies*, no. 30, 2021. https://doi.org/10.52716/jprs.v11i1.432

[55] R. Salazar and M. Ureta-Zañartu, "Mineralization of triadimefon fungicide in water by electro-Fenton and photo electro-Fenton," *Water, Air, and Soil Pollution*, vol. 223, pp. 4199-4207, 2012. https://doi.org/10.1007/s11270-012-1184-7

[56] B. Nayebi and B. Ayati, "Degradation of emerging amoxicillin compound from water using the electro-Fenton process with an aluminum anode," *Water Conservation Science and Engineering*, vol. 6, pp. 45-54, 2021. https://doi.org/10.1007/s41101-021-00101-4

[57] R. Q. Al-Khafaji and A. H. A. Mohammed, "Optimization of continuous electro-fenton and photo electro-fenton processes to treat Iraqi oilfield produced water using surface response methodology," in *IOP Conference Series: Materials Science and Engineering*, 2019, vol. 518, no. 6, p. 062007: IOP Publishing. https://doi.org/10.1088/1757-899X/518/6/062007

[58] H. H. Vigil-Castillo, E. J. Ruiz-Ruiz, K. López-Velázquez, L. Hinojosa-Reyes, O. Gaspar-Ramírez, and J. L. Guzmán-Mar, "Assessment of photo electro-Fenton and solar photo electro-Fenton processes for the efficient degradation of asulam herbicide," *Chemosphere*, vol. 338, p. 139585, 2023. https://doi.org/10.1016/j.chemosphere.2023.139585

[59] D. Clematis and M. Panizza, "Electro-Fenton, solar photoelectro-Fenton and UVA photoelectro-Fenton: Degradation of Erythrosine B dye solution," *Chemosphere*, vol. 270, p. 129480, 2021. https://doi.org/10.1016/j.chemosphere.2020.129480

[60] I. C. Da Costa Soares, R. Oriol, Z. Ye, C. A. Martínez-Huitle, P. L. Cabot, E. Brillas, and I. Sirés, "Photoelectro-Fenton treatment of pesticide triclopyr at neutral pH using Fe (III)–EDDS under UVA light or sunlight," *Environmental Science and Pollution Research*, vol. 28, pp. 23833-23848, 2021. https://doi.org/10.1007/s11356-020-11421-8

[61] A. J. Dos Santos, C. A. Martínez-Huitle, I. Sires, and E. Brillas, "Use of Pt and Boron-Doped Diamond Anodes in the Electrochemical Advanced Oxidation of Ponceau SS Diazo Dye in Acidic Sulfate Medium," *ChemElectroChem*, vol. 5, no. 4, pp. 685-693, 2018. https://doi.org/10.1002/celc.201701238

[62] J. A. Banuelos, O. García-Rodríguez, F. J. Rodriguez-Valadez, and L. A. Godinez, "Electrochemically prepared iron-modified activated carbon electrodes for their application in electro-Fenton and photoelectro-Fenton processes," *Journal of The Electrochemical Society*, vol. 162, no. 9, p. E154, 2015. https://doi.org/10.1149/2.0581509jes

[63] A. Dirany, I. Sirés, N. Oturan, A. Özcan, and M. A. Oturan, "Electrochemical Treatment of the Antibiotic Sulfachloropyridazine: Kinetics, Reaction Pathways, and Toxicity Evolution," *Environmental Science & Technology*, vol. 46, no. 7, pp. 4074-4082, 2012. https://doi.org/10.1021/es204621q

[64] G. Coria, I. Sirés, E. Brillas, and J. L. Nava, "Influence of the anode material on the degradation of naproxen by Fenton-based electrochemical processes," *Chemical Engineering Journal*, vol. 304, pp. 817-825, 2016. https://doi.org/10.1016/j.cej.2016.07.012

[65] A. Wang, Y. Y. Li, and A. L. Estrada, "Mineralization of antibiotic sulfamethoxazole by photoelectro-Fenton treatment using activated carbon fiber cathode and under UVA irradiation," *Applied Catalysis B: Environmental*, vol. 102, no. 3, pp. 378-386, 2011. https://doi.org/10.1016/j.apcatb.2010.12.007

[66] M. D. G. de Luna, M. L. Veciana, C.-C. Su, and M.-C. Lu, "Acetaminophen degradation by electro-Fenton and photoelectro-Fenton using a double cathode electrochemical cell," *Journal of Hazardous Materials*, vol. 217-218, pp. 200-207, 2012. https://doi.org/10.1016/j.jhazmat.2012.03.018

[67] A. C. Crispim, D. M. de Araújo, C. A. Martínez-Huitle, F. L. Souza, and E. V. Dos Santos, "Application of electro-Fenton and photoelectro-Fenton processes for the degradation of contaminants in landfill leachate," *Environmental Research*, vol. 213, p. 113552, 2022. https://doi.org/10.1016/j.envres.2022.113552

[68] I. H. Dakhil and A. S. Abbas, “Preparation, characterization, and performance of potential stainless steel electrodes modified with immobilized semiconductors for persistent organic pollutants via photoelectro-Fenton process”, *Clean Technologies and Environmental Policy*, 1–19, 2025. https://doi.org/10.1007/S10098-025-03334-2

[69] F. H. Kamil, S. K. Barno, F. Shems, A. Jihad, and A. S. Abbas, "Photocatalytic degradation of sulfamethoxazole from a synthetic pharmaceutical wastewater using titanium dioxide (TiO2) powder as a suspended heterogeneous catalyst," *Iraqi Journal of Industrial Research*, vol. 10, no. 1, pp. 26-33, 2023. https://doi.org/10.53523/ijoirVol10I1ID314

[70] S. K. Kamal, Z. M. Mustafa, and A. S. Abbas, "Comparative Study of Organics Removal from Refinery Wastewater by Photocatalytic Fenton Reaction Coupled with Visible Light and Ultraviolet Irradiation," *Iraqi Journal of Industrial Research*, vol. 10, no. 3, pp. 22-32, 2023. https://doi.org/10.53523/ijoirVol10I3ID370

[71] W. Wang, Y. Li, Y. Li, M. Zhou, and O. A. Arotiba, "Electro-Fenton and photoelectro-Fenton degradation of sulfamethazine using an active gas diffusion electrode without aeration," *Chemosphere*, vol. 250, p. 126177, 2020. https://doi.org/10.1016/j.chemosphere.2020.126177

[72] E. J. Ruiz, C. Arias, E. Brillas, A. Hernández-Ramírez, and J. M. Peralta-Hernández, "Mineralization of Acid Yellow 36azo dye by electro-Fenton and solar photoelectro-Fenton processes with a boron-doped diamond anode," *Chemosphere*, vol. 82, no. 4, pp. 495-501, 2011. https://doi.org/10.1016/j.chemosphere.2010.11.013

[73] Ç. Çalık and D. İ. Çifçi, "Comparison of kinetics and costs of Fenton and photo-Fenton processes used for the treatment of a textile industry wastewater," *Journal of environmental management*, vol. 304, p. 114234, 2022. https://doi.org/10.1016/j.jenvman.2021.114234

[74] A. Babuponnusami and K. Muthukumar, "Advanced oxidation of phenol: a comparison between Fenton, electro-Fenton, sono-electro-Fenton and photo-electro-Fenton processes," *Chemical Engineering Journal*, vol. 183, pp. 1-9, 2012. https://doi.org/10.1016/j.cej.2011.12.010

[75] S. Garcia-Segura, L. C. Almeida, N. Bocchi, and E. Brillas, "Solar photoelectro-Fenton degradation of the herbicide 4-chloro-2-methylphenoxyacetic acid optimized by response surface methodology," *Journal of Hazardous Materials*, vol. 194, pp. 109-118, 2011. https://doi.org/10.1016/j.jhazmat.2011.07.089

[76] A. Khataee, A. Khataee, M. Fathinia, B. Vahid, and S. W. Joo, "Kinetic modeling of photoassisted-electrochemical process for degradation of an azo dye using boron-doped diamond anode and cathode with carbon nanotubes," *Journal of Industrial and Engineering Chemistry*, vol. 19, no. 6, pp. 1890-1894, 2013. https://doi.org/10.1016/j.jiec.2013.02.037

[77] F. C. Walsh, L. F. Arenas, and C. Ponce de León, "Developments in electrode design: structure, decoration and applications of electrodes for electrochemical technology," *Journal of Chemical Technology & Biotechnology*, vol. 93, no. 11, pp. 3073-3090, 2018. https://doi.org/10.1002/jctb.5706

[78] L. F. Arenas, C. P. de León, R. P. Boardman, and F. C. Walsh, "Characterisation of platinum electrodeposits on a titanium micromesh stack in a rectangular channel flow cell," *Electrochimica Acta*, vol. 247, pp. 994-1005, 2017. https://doi.org/10.1016/j.electacta.2017.07.029

[79] F. Walsh and C. Low, "A review of developments in the electrodeposition of tin-copper alloys," *Surface and Coatings Technology*, vol. 304, pp. 246-262, 2016. https://doi.org/10.1016/j.surfcoat.2016.06.065

[80] X. Li, D. Pletcher, and F. C. Walsh, "Electrodeposited lead dioxide coatings," *Chemical Society Reviews*, vol. 40, no. 7, pp. 3879-3894, 2011. https://doi.org/10.1039/c0cs00213e

[81] I. Sirés, E. Brillas, M. A. Oturan, M. A. Rodrigo, and M. Panizza, "Electrochemical advanced oxidation processes: today and tomorrow. A review," *Environmental Science and Pollution Research*, vol. 21, pp. 8336-8367, 2014. https://doi.org/10.1007/s11356-014-2783-1

[82] S. Garcia-Segura and E. Brillas, "Applied photoelectrocatalysis on the degradation of organic pollutants in wastewaters," *Journal of Photochemistry and Photobiology C: Photochemistry Reviews*, vol. 31, pp. 1-35, 2017. https://doi.org/10.1016/j.jphotochemrev.2017.01.005

[83] S. O. Ganiyu, C. A. Martínez-Huitle, and M. A. Rodrigo, "Renewable energies driven electrochemical wastewater/soil decontamination technologies: A critical review of fundamental concepts and applications," *Applied Catalysis B: Environmental*, vol. 270, p. 118857, 2020. https://doi.org/10.1016/j.apcatb.2020.118857

[84] S. S. Al-Azawiey, I. H. Dakhel, G. F. Naser, and A. H. Ali, "Photocatalytic Decolorization Simulated Textile Dyebath Effluent under Solar Light and Reuse it for Industrial Propose," *IOP Conference Series: Materials Science and Engineering*, vol. 1090, no. 1, p. 012126, 2021. https://doi.org/10.1088/1757-899X/1090/1/012126

[85] R. Montenegro-Ayo, T. Pérez, M. R. Lanza, E. Brillas, S. Garcia-Segura, and A. J. dos Santos, "New electrochemical reactor design for emergent pollutants removal by electrochemical oxidation," *Electrochimica Acta*, vol. 458, p. 142551, 2023. https://doi.org/10.1016/j.electacta.2023.142551

[86] Y. Lei, Z. Zhan, M. Saakes, R. D. van der Weijden, and C. J. Buisman, "Electrochemical recovery of phosphorus from wastewater using tubular stainless-steel cathode for a scalable long-term operation," *Water Research*, vol. 199, p. 117199, 2021. https://doi.org/10.1016/j.watres.2021.117199

[87] D. Li, T. Zheng, Y. Liu, D. Hou, K. K. Yao, W. Zhang, H. Song, H. He, W. Shi, and L. Wang, "A novel Electro-Fenton process characterized by aeration from inside a graphite felt electrode with enhanced electrogeneration of H2O2 and cycle of Fe3+/Fe2+," *Journal of hazardous materials*, vol. 396, p. 122591, 2020. https://doi.org/10.1016/j.jhazmat.2020.122591

[88] J. Liang, Y. Hou, H. Zhu, J. Xiong, W. Huang, Z. Yu, and S. Wang, "Levofloxacin degradation performance and mechanism in the novel electro-Fenton system constructed with vanadium oxide electrodes under neutral pH," *Chemical Engineering Journal*, vol. 433, p. 133574, 2022. https://doi.org/10.1016/j.cej.2021.133574

[89] R. A. Jassim and S. A. Ammar, "Comparative study for degradation of Congo red dye from synthetic wastewater by photocatalytic redox reactions using various nanoscale semiconductors," *Iraqi Journal of Chemical and Petroleum Engineering* vol. 26, no. 2, pp. 83-91, 2025. https://doi.org/10.31699/IJCPE.2025.2.9

[90] R. Montenegro-Ayo, J. C. Morales-Gomero, H. Alarcon, S. Cotillas, P. Westerhoff, and S. Garcia-Segura, "Scaling up photoelectrocatalytic reactors: a TiO2 nanotube-coated disc compound reactor effectively degrades acetaminophen," *Water*, vol. 11, no. 12, p. 2522, 2019. https://doi.org/10.3390/w11122522

[91] S. McMichael, P. Fernández-Ibáñez, and J. A. Byrne, "A Review of Photoelectrocatalytic Reactors for Water and Wastewater Treatment," *Water*, vol. 13, no. 9, p. 1198, 2021. https://doi.org/10.3390/w13091198

[92] C. Flox, J. A. Garrido, R. M. Rodríguez, P. L. Cabot, F. Centellas, C. Arias, and E. Brillas, "Mineralization of herbicide mecoprop by photoelectro-Fenton with UVA and solar light," *Catalysis Today*, vol. 129, no. 1-2, pp. 29-36, 2007. https://doi.org/10.1016/j.cattod.2007.06.049

[93] J. Peralta-Hernández, Y. Meas-Vong, F. J. Rodríguez, T. W. Chapman, M. I. Maldonado, and L. A. Godínez, "In situ electrochemical and photo-electrochemical generation of the fenton reagent: a potentially important new water treatment technology," *Water research*, vol. 40, no. 9, pp. 1754-1762, 2006. https://doi.org/10.1016/j.watres.2006.03.004

[94] G. De OS Santos, K. I. Eguiluz, G. R. Salazar-Banda, C. Saez, and M. A. Rodrigo, "Testing the role of electrode materials on the electro-Fenton and photoelectro-Fenton degradation of clopyralid," *Journal of Electroanalytical Chemistry*, vol. 871, p. 114291, 2020. https://doi.org/10.1016/j.jelechem.2020.114291

[95] W. Zhou, X. Meng, J. Gao, F. Sun, and G. Zhao, "Janus graphite felt cathode dramatically enhance the H2O2 yield from O2 electroreduction by the hydrophilicity-hydrophobicity regulation," *Chemosphere*, vol. 278, p. 130382, 2021. https://doi.org/10.1016/j.chemosphere.2021.130382

[96] M. Panizza and M. A. Oturan, "Degradation of Alizarin Red by electro-Fenton process using a graphite-felt cathode," *Electrochimica Acta*, vol. 56, no. 20, pp. 7084-7087, 2011. https://doi.org/10.1016/j.electacta.2011.05.105

[97] J. F. Pérez, C. Sáez, J. Llanos, P. Cañizares, C. López, and M. A. Rodrigo, "Improving the Efficiency of Carbon Cloth for the Electrogeneration of H2O2: Role of Polytetrafluoroethylene and Carbon Black Loading," *Industrial & Engineering Chemistry Research*, vol. 56, no. 44, pp. 12588-12595, 2017. https://doi.org/10.1021/acs.iecr.7b02563

[98] S. Garcia-Segura, E. B. Cavalcanti, and E. Brillas, "Mineralization of the antibiotic chloramphenicol by solar photoelectro-Fenton: From stirred tank reactor to solar pre-pilot plant," *Applied Catalysis B: Environmental*, vol. 144, pp. 588-598, 2014. https://doi.org/10.1016/j.apcatb.2013.07.071

[99] S. Garcia-Segura and E. Brillas, "Combustion of textile monoazo, diazo and triazo dyes by solar photoelectro-Fenton: Decolorization, kinetics and degradation routes," *Applied Catalysis B: Environmental*, vol. 181, pp. 681-691, 2016. https://doi.org/10.1016/j.apcatb.2015.08.042

[100] E. Brillas, "Electro-Fenton, UVA photoelectro-Fenton and solar photoelectro-Fenton treatments of organics in waters using a boron-doped diamond anode: a review," *Journal of the Mexican Chemical Society*, vol. 58, no. 3, pp. 239-255, 2014. https://doi.org/10.29356/jmcs.v58i3.131

[101] E. Mousset and D. D. Dionysiou, "Photoelectrochemical reactors for treatment of water and wastewater: a review," *Environmental Chemistry Letters*, vol. 18, no. 4, pp. 1301-1318, 2020. https://doi.org/10.1007/s10311-020-01014-9

[102] J. Xiao, L. Peng, L. Gao, J. Zhong, Z. Huang, E. Yuan, V. Srinivasapriyan, S.-F. Zhou, and G. Zhan, "Improving light absorption and photoelectrochemical performance of thin-film photoelectrode with a reflective substrate," *RSC Advances*, 10.1039/D1RA02826J vol. 11, no. 27, pp. 16600-16607, 2021. https://doi.org/10.1039/D1RA02826J

[103] O. M. Cornejo, M. F. Murrieta, L. F. Castañeda, and J. L. Nava, "Characterization of the reaction environment in flow reactors fitted with BDD electrodes for use in electrochemical advanced oxidation processes: A critical review," *Electrochimica Acta*, vol. 331, p. 135373, 2020. https://doi.org/10.1016/j.electacta.2019.135373

[104] C. Zhang, Y. Jiang, Y. Li, Z. Hu, L. Zhou, and M. Zhou, "Three-dimensional electrochemical process for wastewater treatment: A general review," *Chemical Engineering Journal*, vol. 228, pp. 455-467, 2013. https://doi.org/10.1016/j.cej.2013.05.033

[105] I. S. Michie, J. R. Kim, R. M. Dinsdale, A. J. Guwy, and G. C. Premier, "The influence of anodic helical design on fluid flow and bioelectrochemical performance," *Bioresource Technology*, vol. 165, pp. 13-20, 2014. https://doi.org/10.1016/j.biortech.2014.03.069

[106] B. Wang, G. M. Biesold, M. Zhang, and Z. Lin, "Amorphous inorganic semiconductors for the development of solar cell, photoelectrocatalytic and photocatalytic applications," *Chemical Society Reviews*, vol. 50, no. 12, pp. 6914-6949, 2021. https://doi.org/10.1039/d0cs01134g

[107] D. Sengupta, P. Das, B. Mondal, and K. Mukherjee, "Effects of doping, morphology and film-thickness of photo-anode materials for dye sensitized solar cell application – A review," *Renewable and Sustainable Energy Reviews*, vol. 60, pp. 356-376, 2016. https://doi.org/10.1016/j.rser.2016.01.104

[108] H. Yoo, K. Heo, M. H. R. Ansari, and S. Cho, "Recent advances in electrical doping of 2D semiconductor materials: Methods, analyses, and applications," *Nanomaterials*, vol. 11, no. 4, p. 832, 2021. https://doi.org/10.3390/nano11040832

[109] O. Madkhali, "A review of novel methods to improve the optical and electrical properties of n-type and p-type sulphides and oxides: leading the frontiers of semiconductor technology," *Physica Scripta*, vol. 99, no. 2, p. 022004, 2024. https://doi.org/10.1088/1402-4896/ad1e44

[110] Y. P. Hsiao, W. L. Yang, Y. H. Lin, Y. C. Yang, C. C. Hsu, C. L. Peng, C. H. Liao, F. T. Chin, S. H. Liu, and Y. M. Chang, "Adjustable Switching Voltage Via Sol-Gel Derived and Ag In Situ Doped SiO2 Thin Films for ReRAM," *ECS Transactions*, vol. 53, no. 3, p. 223, 2013. https://doi.org/10.1149/05303.0223ecst

[111] Q.-H. Zhang, X.-R. Deng, W. Yang, H.-H. Hui, Y.-W. Wei, and J.-J. Chen, "Comparative study on cracking behavior of sol-gel silica antireflective coating for high-powered laser system," *Engineering Failure Analysis*, vol. 82, pp. 64-71, 2017. https://doi.org/10.1016/j.engfailanal.2017.08.026

[112] K. Zhang, X. Wang, X. Guo, T. He, and Y. Feng, "Preparation of highly visible light active Fe–N co-doped mesoporous TiO2 photocatalyst by fast sol–gel method," *Journal of Nanoparticle Research*, vol. 16, no. 2, p. 2246, 2014. https://doi.org/10.1007/s11051-014-2246-0

[113] L. F. Pedrini, L. C. Escaliante, and L. V. Scalvi, "Deposition of TiO2 thin films by dip-coating technique from a two-phase solution method and application to photocatalysis," *Materials Research*, vol. 24, no. Suppl 1, p. e20210007, 2021. https://doi.org/10.1590/1980-5373-MR-2021-0007

[114] N. Dhiman and N. Singla, "Smart Nanocoating-an Innovative Solution to Create Intelligent Functionality on Surface," *Chemistry Select*, vol. 9, no. 41, p. e202403038, 2024. https://doi.org/10.1002/slct.202403038

[115] R. A. Sathya and C. Ponraj, "Superhydrophobic route of fabricating antireflective, self-cleaning, and durable coatings for solar cell applications," *Journal of Coatings Technology and Research*, vol. 21, no. 1, pp. 1-30, 2024. https://doi.org/10.1007/s11998-023-00843-x

[116] T. Xia, M. Chen, L. Xiao, W. Fan, B. Mao, D. Xu, P. Guan, J. Zhu, and W. Shi, "Dip-coating synthesis of P-doped BiVO4 photoanodes with enhanced photoelectrochemical performance," *Journal of the Taiwan Institute of Chemical Engineers*, vol. 93, pp. 582-589, 2018. https://doi.org/10.1016/j.jtice.2018.09.003

[117] P. V. Shinde, D. P. Dutta, N. M. Shinde, and R. S. Mane, "Chapter 12 - Electrophoretic deposition of metal oxide nanostructures," in *Solution Methods for Metal Oxide Nanostructures*, R. Mane, V. Jadhav, and A. Al-Enizi, Eds.: Elsevier, 2023, pp. 221-266. https://doi.org/10.1016/B978-0-12-824353-4.00007-5

[118] L. Besra and M. Liu, "A review on fundamentals and applications of electrophoretic deposition (EPD)," *Progress in Materials Science*, vol. 52, no. 1, pp. 1-61, 2007. https://doi.org/10.1016/j.pmatsci.2006.07.001

[119] M. Atiq Ur Rehman, Q. Chen, A. Braem, M. S. P. Shaffer, and A. R. Boccaccini, "Electrophoretic deposition of carbon nanotubes: recent progress and remaining challenges," *International Materials Reviews*, vol. 66, no. 8, pp. 533-562, 2021. https://doi.org/10.1080/09506608.2020.1831299

[120] N. S. Peighambardoust and U. Aydemir, "Electrophoretic deposition and characterization of self-doped SrTiO(3) thin films," (in eng), *Turk J Chem*, vol. 45, no. 2, pp. 323-332, 2021. https://doi.org/10.3906/kim-2007-13

[121] N. Mehta, *Overview of Coating Deposition Techniques* (Tribology Characterization of Surface Coatings). 2022, pp. 1-32. https://doi.org/10.1002/9781119818878.ch1

[122] R. Garg, S. Gonuguntla, S. Sk, M. S. Iqbal, A. O. Dada, U. Pal, and M. Ahmadipour, "Sputtering thin films: Materials, applications, challenges and future directions," *Advances in Colloid and Interface Science*, vol. 330, p. 103203, 2024. https://doi.org/10.1016/j.cis.2024.103203

[123] A. Villamayor, T. Pomone, S. Perero, M. Ferraris, V. L. Barrio, E. G-Berasategui, and P. Kelly, "Development of photocatalytic nanostructured TiO2 and NiO/TiO2 coatings by DC magnetron sputtering for photocatalytic applications," *Ceramics International*, vol. 49, no. 11, Part B, pp. 19309-19317, 2023. https://doi.org/10.1016/j.ceramint.2023.03.058

[124] T. B. Yaqub, T. Vuchkov, P. Sanguino, T. Polcar, and A. Cavaleiro, "Comparative Study of DC and RF Sputtered MoSe2 Coatings Containing Carbon—An Approach to Optimize Stoichiometry, Microstructure, Crystallinity and Hardness," *Coatings*, vol. 10, no. 2, p. 133, 2020. https://doi.org/10.3390/coatings10020133

[125] F. Toma, M. S. Rahman, S. Rahman, K. Hussain, and S. Ahmed, "Thin Film Deposition Techniques: A Comprehensive Review," *J Mod Nanotechnol*, vol. 4, no. 6, 2024. https://doi.org/10.53964/jmn.2024006

[126] A. J. Jawad, "Review on Recent Developments in Coating Procedure by Using Direct Current (DC) Sputtering for Optical Medical Applications," *Pakistan Journal of Scientific Industrial Research Series A: Physical Sciences*, vol. 66, no. 1, 2023.

[127] R. B. A. Souza and L. A. M. Ruotolo, "Electrochemical treatment of oil refinery effluent using boron-doped diamond anodes," *Journal of Environmental Chemical Engineering*, vol. 1, no. 3, pp. 544-551, 2013. https://doi.org/10.1016/j.jece.2013.06.020

[128] O. M. Cornejo, M. F. Murrieta, L. F. Castañeda, and J. L. Nava, "Electrochemical reactors equipped with BDD electrodes: Geometrical aspects and applications in water treatment," *Current Opinion in Solid State and Materials Science*, vol. 25, no. 4, p. 100935, 2021. https://doi.org/10.1016/j.cossms.2021.100935

التحديات والتوجهات المستقبلية في تقنيات فينتون-الكهروضوئية: مراجعة شاملة للتطبيقات والابتكارات الناشئة

إحسان حبيب داخل [١، ٢]، عمار صالح عباس [١، *]

١ قسم الهندسة الكيمياوية، كلية الهندسة، جامعة بغداد، بغداد، العراق
٢ قسم الهندسة الكيمياوية، كلية الهندسة، جامعة المثنى، السماوة، العراق

الخلاصة

يتناول هذا الاستعراض الشامل المبادئ الأساسية والتطبيقات العملية لمعالجة مياه الصرف الصحي الكهروكيميائية غير المتجانسة باستخدام تفاعلات فينتون. وقد تمت مراجعة المعادلات الأساسية المتضمنة توليد الجذور الحرة الهيدروكسيلية في عمليتي فينتون الكهربائية والفوتوفينتون الكهربائية. وقد أثبتت عمليات الفوتوفينتون الكهربائية أنها من أكثر الطرق فعالية في تعدين وتحلل الملوثات في مياه الصرف. وينصب التركيز الرئيسي على فهم قيود عمليات فينتون الهجينة واقتراح طرق فعالة لمواجهة هذه التحديات. بالإضافة إلى ذلك، قيّمت الدراسة أهمية تطوير تكوين الأقطاب الكهربائية وتعزيز اختراق الضوء في زيادة إنتاج بيروكسيد الهيدروجين وزيادة توليد جذور الهيدروكسيل. تساهم هذه التطورات في تحسين تحلل وتمعدن الملوثات في مياه الصرف الصحي الجوفية. ويُظهر تحليل مقارن لمواد الأقطاب الكهربائية، وتكوينات المفاعلات المبتكرة، وظروف التشغيل، العلاقة بين طرق التحضير وكفاءة المعالجة. كما تم تحديد الثغرات البحثية لتحسين عملية الفوتوفينتون الكهربائية، مع اقتراحات للأعمال المستقبلية. أظهرت الدراسات أن الإشعاع الضوئي الداخلي يؤدي إلى كفاءة إزالة أعلى مقارنةً بأنظمة الإضاءة الخارجية بنفس قوة مصدر الضوء. وكانت أهم التوصيات استخدام مفاعلات متعددة الأقطاب الكهربائية لتقليل استهلاك الطاقة، وتعزيز كفاءة التيار، كما يلعب شكل الأقطاب الكهربائية دورًا حيويًا في زيادة تعرض أسطح الأقطاب الضوئية لأشعة الضوء، وإجراء تجارب طويلة الأمد على ملوثات مختلفة لإثبات استقرار المفاعل وكفاءته وفعاليته في معالجة مياه الصرف الصناعي.

الكلمات الدالة: ترتيبات الأقطاب الكهربائية، المفاعلات المبتكرة، عمليات فنتون الهجينة، طرق الطلاء، تحديات فينتون.