J. Electrochem. Sci. Eng. **16** (2026) 3042; https://doi.org/10.5599/jese.3042

Open Access : : ISSN 1847-9286
https://pub.iapchem.org/ojs/index.php/JESE

Review paper

Advances and challenges of SnO_2-based anodes for electrochemical wastewater treatment

Ghaidaa A. Ismael and Ali H. Abbar✉

Department of Biochemical Engineering, Al-Khwarizmi College of Engineering, University of Baghdad, Baghdad, 10071, Iraq

Corresponding Author: ✉*ali.abbar@kecbu.uobaghdad.edu.iq*; Tel.: +9647803280891

Received: October 8, 2025; Accepted: June 16, 2026; Published: July 13, 2026

Abstract

SnO_2-based anodes have been widely used in heterogeneous catalytic processes, particularly in the anodic oxidation of wastewater containing recalcitrant organic materials. This review covers the application of SnO_2-based anodes for the treatment of various wastewater sources, including phenols, dyes, landfills, and petroleum refinery wastewater, via direct anodic oxidation. The key operating parameters affecting anodic oxidation are summarized, the oxidation process mechanisms are elucidated, and typical methods for preparing these electrodes are described. This comprehensive review demonstrates that SnO_2-based anodes can efficiently degrade organic pollutants in wastewater and confirms their high oxidation capacity and dimensional stability. Despite these excellent properties, the performance and durability can be further enhanced via novel doping strategies, innovative fabrication methods, and hybrid material designs, such as combining SnO_2 nanotubes with TiO_2 nanotubes. These emerging approaches provide pathways for the scalable and energy-efficient deployment of SnO_2-based anodes in industrial wastewater treatment and sustainable operation applications.

Keywords

Pollutant removal; electrochemical oxidation; tin(IV) oxide electrodes; electrode preparation methods; electrode stability; reactor design

Introduction

Currently, wastewater treatment management is considered a complex problem and a decisive factor in evaluating the sustainable improvement of recent industrial practices and applications, with basic measures being important for achieving a clean environment. Most environmental contaminants can be successfully removed or converted into new nontoxic products using one or more treatment methods, including physical, biological, and chemical approaches. Depending on the quality of the polluted water and the chemical composition of the existing organic compounds,

wastewater treatment methods are complex and variable. Compared with biological and physical methods, the removal of contaminants *via* chemical approaches is more efficient and easier to control. Contaminant removal techniques have received widespread attention for treating various types of wastewater. Furthermore, because industrial waste frequently comprises inorganic and organic compounds with highly diverse characteristics, a broad treatment strategy is not feasible [1].

The typical technologies used to generate these radicals include electrical discharge processes, thermal activation, chemical reaction pathways, catalytic reactions, illumination/irradiation, and electrochemical activation [2,3].

Numerous advanced oxidation processes (AOPs) have been used to treat wastewater (Figure 1). Electrocatalytic oxidation (anodic oxidation) has attracted considerable interest for treating wastewater and is considered an excellent approach for degradation, especially for contaminants that are extremely resistant to oxidation [4].

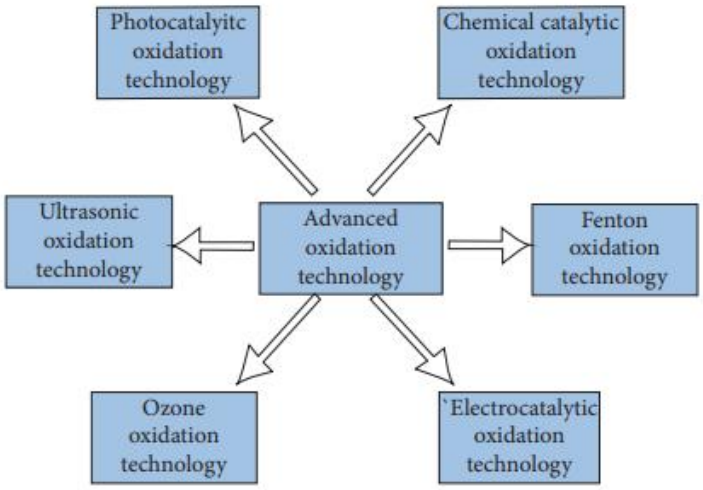

Figure 1. *Classification of advanced oxidation technologies. Reproduced from [4] Article ID 2107939, licensed under CC BY*

Anodic oxidation is a more efficient and eco-friendly method than other electrochemical processes because it does not require large amounts of chemicals, thereby reducing the production of secondary contaminants; thus, no additional accessories should be required. However, anode materials represent the major factor affecting the efficiency of anodic oxidation. Many researchers have tested various anodic materials, such as glassy carbon [5], RuO_2 [6], Pt-Ir [7], fibre carbon [8], manganese dioxide [9], Pt-carbon black [10], porous carbon felt [11], stainless steel [12], reticulated vitreous carbon [13], boron-doped diamond (BDD) [14] and SnO_2 [4]. Among these types, tin oxide (SnO_2) is considered a powerful, cost-effective, and eco-friendly anodic material for treating wastewater [4]. Table 1 compares SnO_2-based anodes and other relevant electrodes used in wastewater in terms of chemical oxygen demand (COD) removal, stability, current efficiency, and energy consumption. The comparison confirms that SnO_2-based anodes are considered the second-best option after BDD [15-17].

Based on the comparisons presented above, this review will further investigate the application of anodic oxidation for wastewater treatment, the influence of key parameters on the efficiency of this process, and the ability of SnO_2-based electrodes to serve as effective anodic materials. The properties, preparation methods, stability, and application of these materials for treating various types of wastewater are described to provide a comprehensive understanding of the importance of these anodes. The challenges in their applications and future improvements are also presented.

Table 1. *Comparison of SnO_2-based anodes with relevant anodic materials in wastewater treatment*

Anode type	Typical COD removal, %	Stability	Energy consumption, kWh kg^{-1} COD	Current efficiency, %	Remarks
SnO_2-based anodes	60 to 95 (according to characteristics of wastewater)	Good but variable	8 to 14 (in many papers; can be reduced by doping)	5 to 30 (moderate)	Cost-effective anodic materials and easy to fabricate
BDD anodes	Higher than 85 based on wastewater type	High and robust	~1.5	Over 40 (decreases in performance as current density increased)	High cost and difficulty of adoption in the manufacturing industry
PbO_2 anodes	70 to 90 based on wastewater type	Moderate	Variable, higher than that in BDD	Moderate	Pb leaching during operation (toxic impact)
Mixed metal oxide, such as RuO_2/IrO_2	50 to 90 based on wastewater type	Good	8.7 to 11.4	Moderate	Cost of noble metals is a factor

Wastewater treatment by electrochemical oxidation

Mechanism of anodic oxidation

Anodic oxidation of organic contaminants present in wastewater can be accomplished *via* two routes: direct and indirect oxidation. Organic compounds can be oxidized directly at the anode surface *via* electron transfer, which generates physisorbed or chemisorbed $^{\bullet}OH$ radicals from either hydroxyl ion or water oxidation (Equations (1) and (2)) [4].

$$OH^- \rightarrow {}^{\bullet}OH + e^- \quad (1)$$

$$H_2O \rightarrow {}^{\bullet}OH + H^+ + e^- \quad (2)$$

This route is called direct anodic oxidation. In the other route (indirect anodic oxidation), organic compounds are degraded in the bulk of a solution by oxidizing reagents generated anodically, where O_3, Cl_2, ClO^-, peroxide, and persulfate act as mediators for oxidizing organic compounds [18]. Reactive chlorine species, such as Cl_2, ClO^- and HClO, are produced from the oxidation of chloride ions (Equations (3) to (5)) and represent the most active mediator because high-concentration chlorine ions already exist in wastewater [19].

$$2Cl^- \rightarrow Cl_2 + 2e^- \quad (3)$$

$$Cl_2 + 2H_2O \rightarrow 2HClO^- + 2H^+ + 2e^- \quad (4)$$

$$Cl^- + 2OH^- \rightarrow ClO^- + H_2O + 2e^- \quad (5)$$

Figure 2 illustrates the mechanism of anodic oxidation on mixed metal oxide anodes.

Direct anodic oxidation is an attractive approach because no chemicals that can generate secondary pollution are added [20,21]. However, this method may suffer deactivation due to the formation of a polymer layer on the anode surface [6].

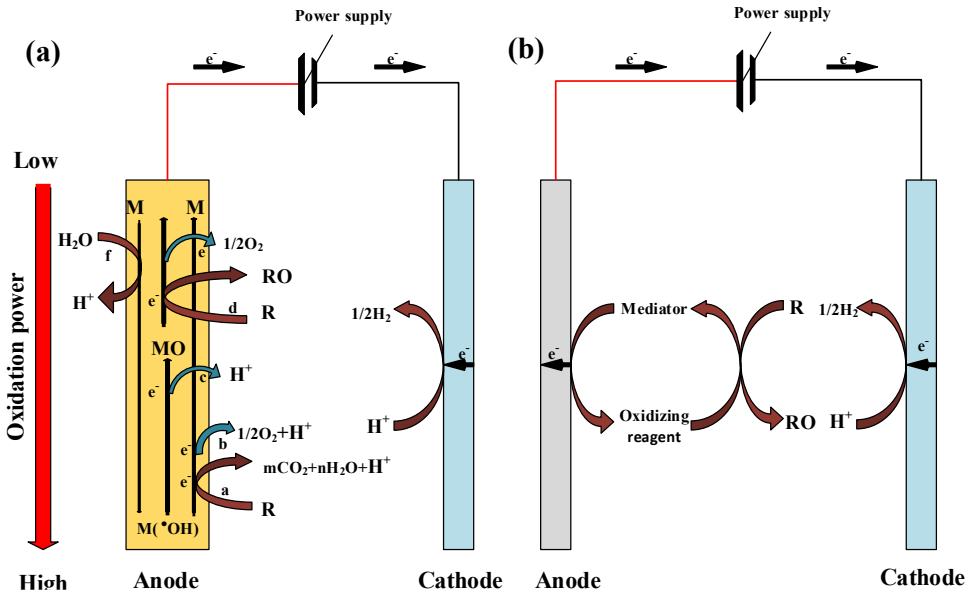

Figure 2. *Mechanistic schemes of anodic oxidation: (a) direct method and (b) indirect method. Redrawn by the authors based on ref.[18]. Notes: R, target pollutants; MO, mixed metal oxide anode with chemisorbed active oxygen; M(•OH), mixed metal oxide with physically adsorbed active oxygen*

Parameters affecting anodic oxidation

Various operating conditions influence the removal of organic contaminants by anodic oxidation in aqueous solutions. The most common operating conditions include the nature of the supporting electrolyte and its concentration, current density, pH, initial concentration of organic contaminants, temperature, and presence or absence of metallic cations [21,22].

Impact of supporting electrolyte

The commonly used supporting electrolytes include NaCl, $NaNO_3$, $NaClO_4$, Na_2SO_4, Na_2CO_3 and KCl [23]. Asim *et al*. [24] used 3D-Ti/Sb-SnO_2-Gr electrodes and adopted two types of supporting electrolyte, namely, KCl and Na_2SO_4, to evaluate the effect of the supporting electrolyte on the degradation efficiency of 2,4-dichlorophenol (2,4-DCP). The degradation rate was faster with KCl, with a removal efficiency of 83 %, whereas it was 81 % with Na_2SO_4 (Figure 3).

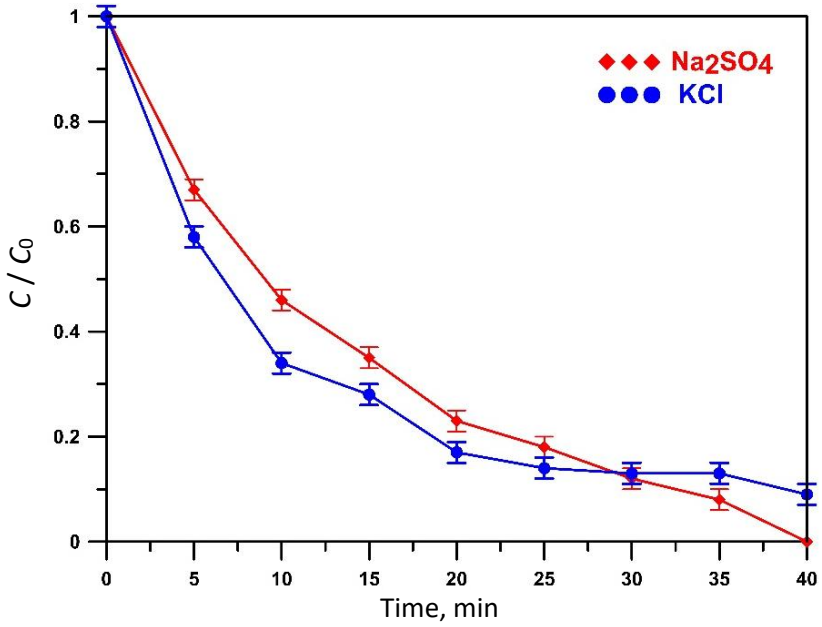

Figure 3. *Effect of supporting electrolyte on the degradation of 2,4-DCP by 3D-Ti/Sb-SnO_2-Gr electrodes in 0.5 M Na_2SO_4 and KCl. Redrawn by the authors based on ref.[24]*

However, at longer times, the removal efficiency can reach 99.9 % for Na_2SO_4, and direct anodic oxidation by •OH is primarily responsible for the degradation of 2,4-DCP.

Li *et al*. [25] examined the effect of supporting electrolytes on the degradation of aniline using different tin oxide anodes (Figure 4). The colour changed during electrolysis, *i.e*., the colour of the electrolyte first turned light brown, followed by dark brown, light yellow, and finally, colourless in both electrolytes. A dark brown colour appeared at 1 h in the case of Na_2SO_4 and at 0.5 h in the case of NaCl for Ti/Sb-SnO_2. Their findings confirmed the fast removal of aniline in the NaCl electrolyte.

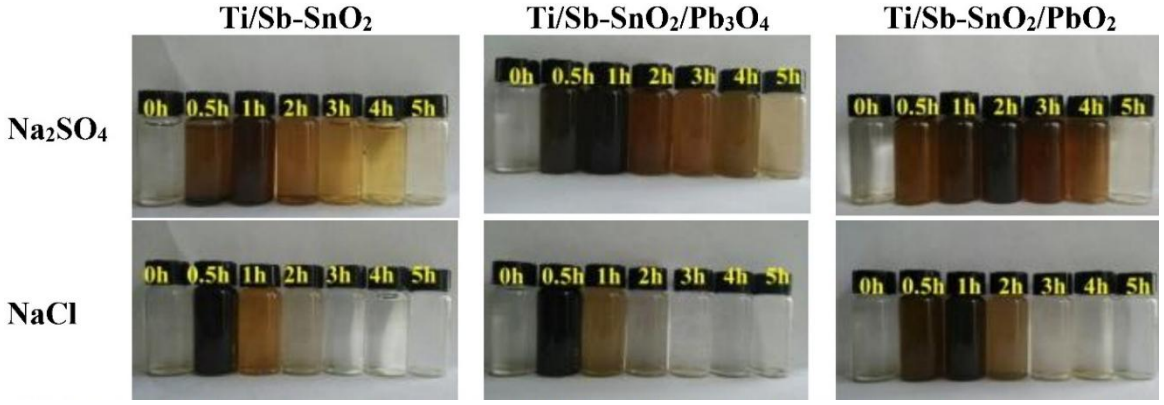

Figure 4. *Effect of the supporting electrolyte on aniline removal using different types of tin oxide anodes. Operating conditions: current density of 20 mA cm^{-2}, 500 mg L^{-1} aniline and 5 wt.% of supporting electrolytes. Redrawn by the authors based on ref.[25]*

Impact of organic pollution concentration

An essential parameter in the removal of organic contaminants *via* anodic oxidation is the initial pollutant concentration. Zhou *et al*. [26] examined how the initial concentrations of benzophenone-3 (BP-3) and its intermediate (4-OH-BP) affect the rate at which they are degraded. The rate constant (k) values of BP-3 were 0.236, 0.175, 0.083, 0.052 and 0.035 min^{-1} at initial concentrations of 2, 5, 10, 20 and 40 mg L^{-1}, respectively; for 4-OH-BP, the corresponding k values were 0.308, 0.205, 0.113, 0.063 and 0.028 min^{-1} at initial concentrations of 2, 5, 10, 20 and 40 mg L^{-1}, respectively. Increasing the starting concentration prevented BP-3 and 4-OH-BP from degrading (Figure 5).

The influence of the starting concentration on the removal efficiency has been the topic of many studies [27,28]. Their findings showed that high pollutant removal rates can be achieved at low concentrations.

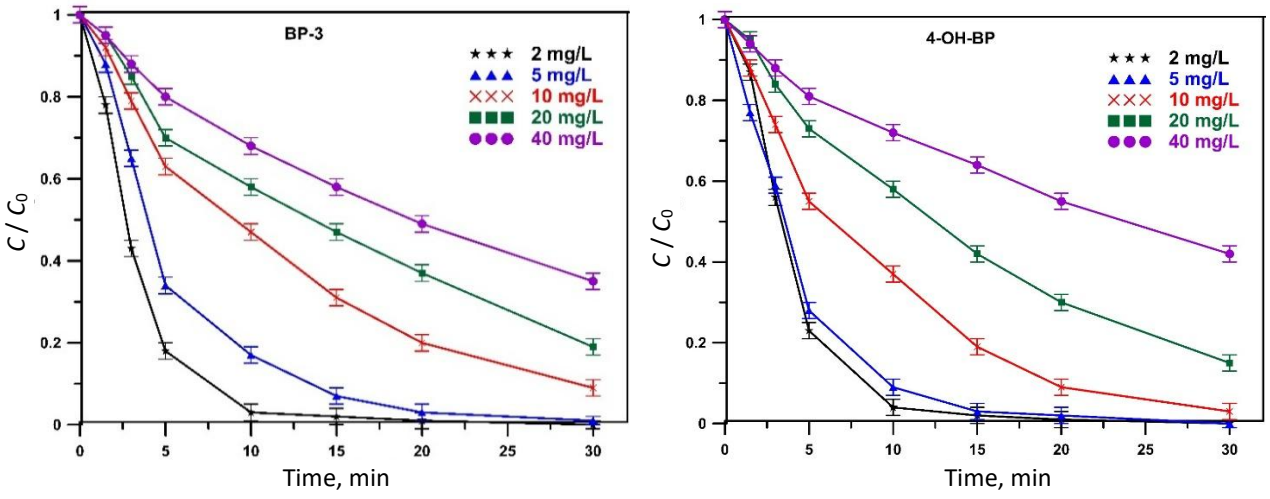

***Figure* 5.** *Influence of the initial concentrations of BP-3 and 4-OH-BP on removal efficiency via anodic oxidation. Redrawn by the authors based on [26]*

Impact of current density

An appropriate selection of current density within the anodic oxidation system preserves a specific level of current efficiency while eliminating contaminants and decreasing energy consumption [29]. Li *et al.* [30] used Ti/Sn-Sb/PbO_2 in their treatment study on coal gasification wastewater (CGW) at current densities ranging between 20 and 60 mA cm^{-2}. The reduction in the TOC level of CGW at various current densities is shown in Figure 6. The ability of the electrocatalytic oxidation system to remove TOC increased markedly with current density, but the reaction rate slowed due to rapid consumption and oxygen evolution (side reactions) of the reactants.

Abd and Abbar [31] evaluated the performance of a Cu/SnO_2-Sb_2O_5 anode electrode for COD removal in hospital wastewater at different current densities (5, 10, and 15 mA cm^2) (Figure 7).

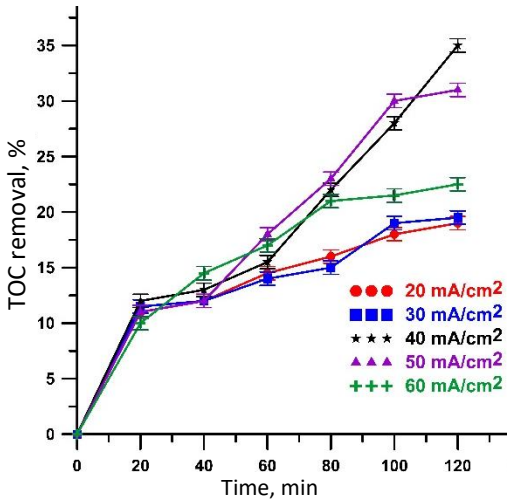

Figure 6. *Mineralization of coal gasification wastewater (CGW) at different current densities. Redrawn by the authors based on [30]*

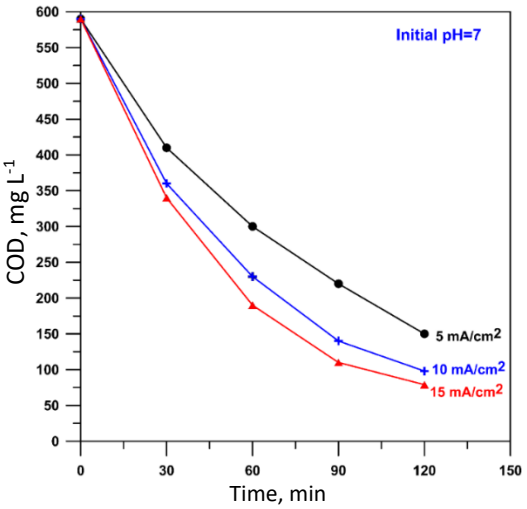

Figure 7. *Influence of current density on the decay of COD during electro-oxidation of hospital wastewater using a Cu/SnO_2-Sb_2O_5 anode Reproduced from [31], licensed under CC BY 4.0*

Past studies have shown that increasing the current density improves the COD removal efficiency (74.6 to 86.6 %) and increases the current density (to 15 mA cm^{-2}). However, this efficiency improvement is accompanied by a significant increase in energy consumption (from 1.43 to 6.13 kWh kg^{-1} COD) at the aforementioned current density.

Effect of the initial solution pH

Many researchers have examined how the initial pH influences the degradation process. Past findings suggest that the initial pH is vital for the electrocatalytic degradation of organic compounds. As pH can alter the catalyst surface charge in wastewater treatment and the morphology of degraded species, solution pH is frequently a key parameter influencing the removal of organic pollutants [32,33]. However, results from prior work varied, even contradicting one another, which may be attributed to differences in the electrode materials examined and in the structures of the organic pollutants. Cao *et al.* [28] used Ti/SnO_2-Sb-Cu to investigate the effects of the initial pH on the colour and COD removal of methylene blue (MB) (Figure 8) and found that a high removal of COD could be obtained at a low pH. Abd and Abbar [31] used Cu/SnO_2-Sb_2O_5 to examine the effect of initial pH on the COD removal efficiency from hospital wastewater, and three pH values (3, 7 and 9) were evaluated at a constant current density of 10 mA cm^{-2} (Figure 9). A pH of 3 resulted in the highest COD removal efficiency of 85 %, whereas a pH 9 resulted in the lowest removal efficiency of 79.66 %.

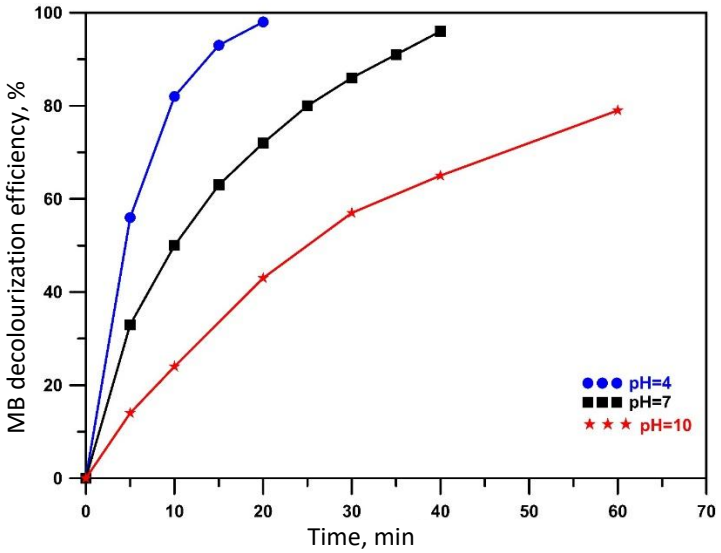

Figure 8. *Effect of initial pH on the decolorization efficiency of methylene blue (MB). Redrawn by the authors based on [28]*

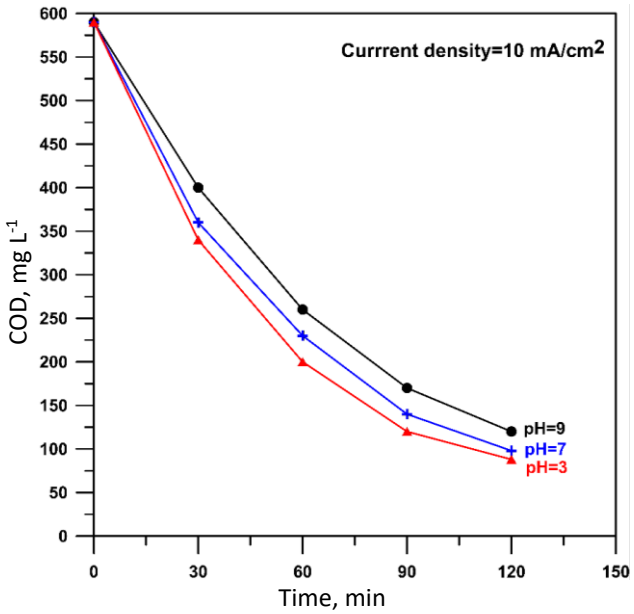

Figure 9. *Influence of pH on COD decay during electro-oxidation of hospital wastewater using a Cu/SnO_2-Sb_2O_5 anode. Reproduced from [31], licensed under CC BY 4.0*

Temperature effects

Panizza *et al*. [34] used BDD anodes to investigate the influence of temperature on COD and color removal during the direct oxidation of MB. Increasing the temperature from 20 to 40 °C effectively removed COD. Un *et al.* [35] used Ti/RuO_2 anodes and found that organic removal rates increased with increasing temperature during the electrochemical oxidation of olive mill wastewater. The temperature did not affect direct oxidation but strongly influenced indirect oxidation when the aforementioned two parameters were considered simultaneously.

Typical designs of electrochemical reactors

The optimal design of electrochemical reactors (ECRs) is the most important factor in the successful operation of electrochemical oxidation of organic pollutants, as it can increase process efficiency and reduce energy requirements. The design and configuration of ECRs directly influence the mass and heat transfer mechanisms and the fluid flow and mixing within reactors [36]. Recent studies provide

evidence of advancements in ECR designs, and optimizations of these configurations have focused on improving mass-transfer efficiency by increasing the contact area between fluids and electrodes; however, most of these configurations are still at the laboratory stage or at the pilot scale [37]. During the design stage of ECR, many criteria should be considered. First, the design procedure should comply with electrocatalytic requirements and be highly feasible, with simple operation and maintenance; second, the electrode material should be readily available and easy to use, and the reactor should be environmentally friendly and versatile [36].

In general, ECRs can be classified based on the reactor structure, mode of operation, flow type, and electrode configuration (Figure 10).

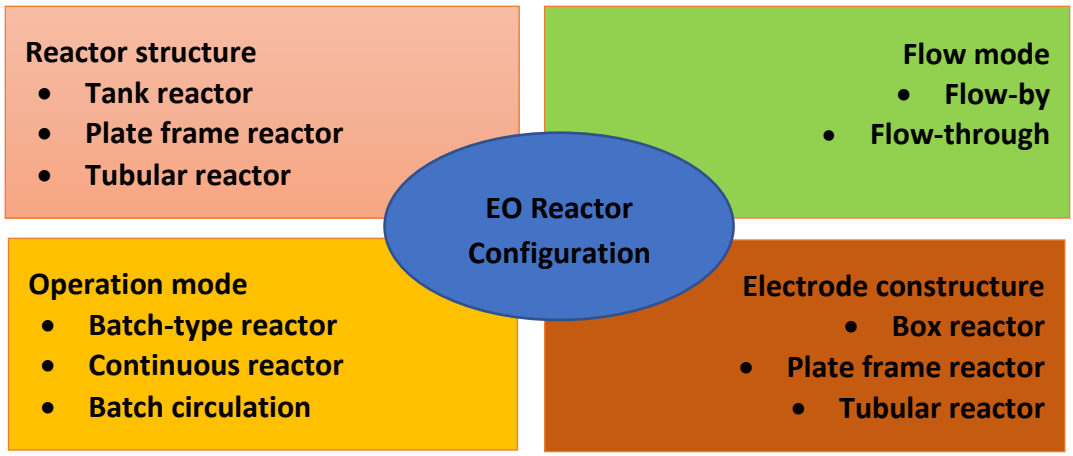

Figure 10. *Reactor configurations of ECRs Reproduced from [37], licensed under CC BY 4.0*

The simplest ECR configuration is a tank reactor with two plate electrodes inserted into a rectangular tank. This design is widely used for wastewater treatment due to its simplicity. However, tank reactors are difficult to apply at industrial scales due to their small volume and short-duration operation, as well as the difficulty of determining the impacts of mass transport and flow regimes [38]. Reactors with distinctive designs, such as filter-press ECRs (plate-frame reactors) and tubular ECRs, have been designed to improve spatiotemporal efficiency and enhance mass transfer. The plate-frame reactor usually consists of many plates as electrodes, with frames enclosing them in a parallel configuration [39]. Compared with the tank type, the plate-frame ECR has a higher space utilization rate, lower pressure loss, and lower cell potential due to the closer electrode spacing, indicating decreased energy consumption [40]. Tubular ECRs use tube-shaped electrodes in a tank. The traditional type consists of an anode rod inside an outer cathode tube, forming a concentric tubular cell. Compared with water in the tank-type design, the water in the traditional type has a more uniform current distribution and higher polarity [36]. Tubular ECR has been successfully used to degrade organic contaminants in wastewater, particularly highly concentrated contaminants, such as pharmaceutical, petroleum refinery, dye, and food manufacturing wastewater [41-44]. Recently, rotating electrodes and turbulence promoters have received widespread attention [36]. With respect to the mode of operation, ECRs can operate in batch, batch-circulation, and continuous modes. In the first two modes, the ECR is operated for a fixed time by cycling until the required level of pollutant degradation is attained. These two modes are appropriate for small-scale pollutant treatment, but they suffer from low treatment capacity. Continuous ECRs are typically operated in single-pass mode, with contaminants in the influent contacting the electrodes in series or parallel. The continuous mode is preferable from an engineering perspective because it offers numerous benefits, such as cleaner products, faster reactions, and greater safety and ease of scale-up,

compared with batch reactors [37]. In general, 2D and 3D electrodes are used for anodic oxidation. The 3D-ECR is composed of a granulated material packed as a bed between a 2D flat-plate electrode and operates in flow-through or flow-by mode [45]. The bed can be fixed or fluidized, with the latter providing a larger activation area and a higher mass transfer rate [46].

SnO_2-based electrodes

Properties of SnO_2

Two oxidation states of tin (Sn) exist because of its dual valence. The first is 2+, represented by stannous oxide (SnO), whereas the second is 4+, represented by stannic oxide (SnO_2) [47,48]. SnO_2 has a tetragonal rutile structure with space group D4h14 (P42/mnm) [47]. One unit cell is composed of six atoms, two of which are Sn and four of which are oxygen [48].

Pure SnO_2 has high electrical resistance; thus, it is unsuitable for electrode fabrication [49-51]. However, when SnO_2 is mixed with Ar, B, Bi, F, P and Sb, its conductivity increases significantly [52-55]. Antimony (Sb) is commonly used as a dopant in anodic oxidation applications [56,57]. Transparent electrodes composed of doped SnO_2 films are found in a variety of applications, including gas detectors, high-efficiency solar cells, transparent heating elements, and far-infrared detectors [58]. SnO_2 doped with Sb is classified as a "nonactive" anode because of its high O_2 evolution overpotential, which results in poor catalysis for O_2 evolution reactions. However, this feature encourages the conversion of organic matter to CO_2 [59]. Sb-doped SnO_2 electrodes are efficient for wastewater treatment, particularly for the oxidation of organic compounds [60,61]. Another benefit of using SnO_2 is its lower cost compared with other precious materials, such as platinum and BDD [62].

Methods for fabricating SnO_2 electrodes

Various methods for preparing Ti/SnO_2-Sb electrodes, such as sol-gel, thermal decomposition, hydrothermal, electrodeposition, sputtering, dip-coating, ultrasonic atomization decomposition, and self-assembly, are currently available. Different preparation methods affect the microstructure and performance of the Ti/SnO_2-Sb electrode [63,64]. Table 2 presents the various manufacturing methods and their methodologies and characteristics.

Table 2. *Methods for preparing tin oxide anodes*

Manufacturing method	Methodology	Characteristics
Chemical vapor deposition	SnO_2 film produced *via* vapor phase caused by chemical reactions	High cost with uniform surface
Thermal decomposition	High temperature is applied to decompose Sn-precursor	Low cost but needs many multilayer coatings
Hydrothermal	High temperature is applied under high pressure	Ability to produce pure and highly crystalline material but entails high cost
Sol-gel dip-coating technique	High temperature is applied without a colloid solution	Low cost but needs many multilayer coatings
Spray pyrolysis	A precursor solution is deposited on surface of electrode under carrier gas	High cost with a uniform surface
Electrodeposition	Tin oxide films are deposited on anodic or cathodic electrodes	Low cost but produces nonuniform deposition

Chemical vapor deposition

Chemical vapor deposition (CVD) was used to deposit a high-purity tin oxide thin film. The ingredients in the vapor phase were mixed in a reaction chamber, and a chemical reaction was induced, causing the mixture to be adsorbed onto a heated substrate, yielding a solid film [4]. The temperature of the substrate is important because it affects the formation of various reactions. Changing the gas phase composition can also produce a variety of gradients or variable coatings [4]. Yao *et al.* [63] applied CVD to create Ti/SnO_2 anodes at 550 °C from a precursor composed of $SnCl_4$ and H_2O as a gas phase mixture. The electrodes exhibited a high overpotential for O_2 evolution, a compact microstructure, and good activity toward contaminant oxidation. The surface quality of the electrode prepared by this method could be controlled, but the high cost of precursor materials limited their use in Ti/SnO_2-Sb synthesis. Scott *et al.* [64] used mist CVD to create SnO_2-Sb thin films, thereby reducing the cost and throughput limitations of the CVD method (high-vacuum technique). This technique was based on a nonvacuum, solution-based method that included aerosol-aided transport using ultrasonically generated aerosols from simple precursors composed of aqueous Sn and Sb. Another technique called combustion CVD was used to prepare SnO_2 on a quartz substrate at atmospheric pressure with heating set to 850 to 1150 °C [65].

Thermal decomposition

The thermal decomposition method is based on the heat treatment of tin and antimony chlorides on a titanium electrode. Chlorides are dissolved in isopropanol to prepare a precursor solution. The surface of the titanium sheet (substrate) is coated with the precursor solution, placed in an oven, and heated. As chlorides are unstable at high temperatures, they are converted to mixed oxides. In general, the thermal decomposition method consists of three steps: substrate pretreatment (Ti), application of the coating precursor solution, and thermal treatment [66,67].

Sol–gel dip-coating technique

The sol–gel dip-coating approach can be achieved by dissolving $SnCl_2{\cdot}2H_2O$ and $SbCl_3$ in absolute ethanol and separately stirring and heating the two solutions in closed vessels, followed by evaporating them until dryness to obtain two powders. In a previous study, two powders were mixed in ethanol at the doping ratio, with stirring and heating at 50 °C for 2 h [68]. The substrate was dipped in the obtained solution, dried at 100 °C, re-dipped into the solution, dried, and heated at 600 °C [68-70]. Different precursors, such as $SnCl_4$ and tin alkoxide, can be used as reacting materials when fabricating SnO_2 nanostructures, and colloidal nanoparticles can be combined with a chemical solution (*i.e*. sol) to form a gel (an integrated network) [70]. However, the use of tin alkoxides is avoided because of their high cost and high moisture sensitivity. By contrast, the use of $SnCl_4$ as a precursor entails low-cost and simple control processes. In conclusion, despite the ability of the sol–gel process to prepare SnO_2 nanoparticles [70,71] and nanotubes [72], the morphologies of the nanostructures are constrained by the difficulty of template fabrication, especially when various shapes and sizes are considered.

Spray pyrolysis

Correa-Lozano *et al*. [73] employed spray pyrolysis to prepare Ti/SnO_2-Sb_2O_5 anodes, using N2 as the carrier gas. The precursor solution was prepared by dissolving $SnCl_4{\cdot}5H_2O$ and $SbCl_3$ in an ethanol/HCl (32 %) solvent. The nozzle was positioned 17 cm away from the substrate, and the temperature was set between 400 and 700 °C. Thin films of nanostructured SnO_2 were deposited on glass substrates by spray pyrolysis using a precursor composed of $SnCl_4{\cdot}5H_2O$ [74,75]. The

product was polycrystalline with a pure phase. Ong *et al*. [75] used spray pyrolysis with a precursor composed of $SnCl_4 \cdot 5H_2O$ to synthesize thin films of nanostructured SnO_2 deposited on glass substrates. Increasing the precursor concentration improved the grain size of the films. Furthermore, the growth of the film started at temperatures above 270 °C. Hence, the substrate temperature plays an essential role in film formation and crystallinity.

Hydrothermal treatment

In recent years, hydrothermal synthesis has been widely used to prepare nanomaterials, thereby improving microstructures and increasing surface areas. Researchers have attempted to apply this method to prepare DSAs. Deng *et al.* [76] prepared a Ti/SnO_2-Sb anode with a microsphere structure composed of nanosheets *via* a hydrothermal method. The prepared electrode was compared with a sample prepared by thermal decomposition for MB removal. The results confirmed that the MB removal rate reached 100 % with the designed electrode, and its performance was significantly superior to that of the thermal decomposition electrode. Man *et al*. [77] fabricated a tin oxide (SnO_2) electrode in two steps: a hydrothermal method to form tin oxide nanostructures, followed by a thermal decomposition method to incorporate cerium and antimony into the nanostructures. The Ti/Ce−Sb−SnO_2 NF anode performed excellently at removing organic contaminants, such as MB. The proposed technique achieved a colour removal efficiency of up to 100 % and a mineralization efficiency of up to 91.45% within 90 minutes, demonstrating its greater stability and longer lifetime than those of techniques using non-doped electrodes.

Electrodeposition

Electrodeposition, considered a superficial approach for preparing tin oxide anodes, has been applied extensively. The deposition conditions, including the Sn source, pH, current density, and temperature, substantially affected the surface morphology of the dispersions and their adhesion properties [4].

a) Anodic methods

SnO_2 films were synthesized by anodizing Sn sheets in a voltage range of 6 to 50 V with an ethylene glycol-based electrolyte [78]. SnO_2 substrates were crystallized at temperatures below 200 °C, and the thicknesses of the polycrystalline structure ranged between 250 and 690 nm [78]. The process of producing tin foils with a mesoporous SnO_2 spherical structure and a tuneable particle size was also investigated (*i.e.* the sample was electrochemically anodized in an electrolyte composed of NH_4F and NaOH in ethylene glycol) [79]. Yamaguchi *et al.* [80] prepared a tin oxide film by electrochemically anodizing a tin film deposited on a fluorine-doped tin oxide electrode. Columnar-type pore-channel tin oxide films (50 nm) with optical transparency were successfully obtained in other studies [81,82].

b) Cathodic methods

Chang *et al*. [83] synthesized nanostructured SnO_2 films on a copper substrate *via* cathodic deposition. Films with relatively low crystallinity were deposited at 85 °C. After thermal treatment under vacuum for 4 h at 400 °C, the SnO_2 nanocrystals formed a structure with a grain size of 4 to 7 nm and were composed of a tetragonal configuration. Porous surface films were prepared at current densities of 5-15 mA cm^{-2}. Other conditions for fabricating nanocrystalline two-layered SnO_2 coatings from HNO_3 solutions at 85 °C were also investigated [84-86].

Lai *et al*. [87] used a rigid template of nanoporous polycarbonate membranes in 1D nanostructures for the electrodeposition of SnO_2 nanotubes. Spray and Choi [88] investigated the use of surfactants, such as sodium dodecyl sulphate (SDS); introduced SDS to form Sn^{4+} ions with a well-

ordered arrangement, serving as the skeleton of the SnO_2 film; and produced mesoporous frameworks *via* cathodic deposition [89].

Stability/degradation of SnO_2-based electrodes

The long-term stability of SnO_2 anodes remains a major obstacle to their industrial application due to the interplay of multiple degradation mechanisms under typical anodic polarization conditions. The deactivation of SnO_2 anodes can be attributed to a variety of factors, such as the formation of a resistive layer separating the coatings from the substrate, the formation of a passive layer over the external coating, or the selective loss of the catalyst to the electrolyte. Furthermore, the SnO_2-Sb_2O_5 electrodes undergo deactivation when nonconductive films of $Sn(OH)_2$ form on the surface of the anodes [62]. The electrochemical dissolution of SnO_2, particularly at high oxidation potentials and in acidic environments, is a major failure pathway, as Sn(IV) can become unstable and be released as ions (Sn^{2+}/Sn^{4+}). The effect of this process is amplified in the presence of structural defects, grain boundaries, and complex anions, leading to a gradual decrease in the thickness of the SnO_2 layer and eventual exposure of the substrate [90].

Interfacial oxidation at the titanium-tin oxide (Ti/SnO_2) contact surface, another pathway for anode failure, plays a crucial role in anode disruption caused by coating defects such as micropores or microcracks. In these cases, the titanium substrate undergoes direct anodic oxidation, thereby forming an insulating titanium dioxide (TiO_2) layer that increases interfacial resistance and contributes to coating detachment [91]. Surface passivation is another failure pathway. In this case, the adsorption of polymer compounds formed by the oxidation of organic pollutants during anodic oxidation blocks active sites and inhibits the generation of hydroxyl radicals. These reactions result in partial rather than complete oxidation, increasing energy consumption [92]. The leaching of dopants, particularly antimony and lead, is a crucial aspect, as they are typically added to enhance the electrical conductivity and catalytic activity of tin oxide. Under prolonged electrolysis, pentavalent antimony (Sb^{5+}) may be reduced to the more soluble trivalent antimony ions (Sb^{3+}), while lead dissolves as divalent lead ions (Pb^{2+}). These reactions decrease electrical conductivity and catalytic efficiency, raising environmental concerns due to the release of toxic ions [92].

The aforementioned degradation pathways are closely interconnected: dopant leaching reduces thin-layer conductivity, causing a localized overvoltage that accelerates tin dissolution; thinning of the layer increases the substrate's susceptibility to oxidation; and surface passivation increases the required operating voltage, intensifying the corrosion process. Thus, the degradation of tin oxide (SnO_2) anodes is inherently nonlinear and often characterized by an initial quasi-stable state, followed by a rapid decrease in performance [92].

Integrating degradation pathways with material design strategies is crucial for improving the stability of tin dioxide-based anodes. Tin dissolution, resulting from high anodic potentials and poor lattice stability, can be effectively reduced by doping with polyvalent elements (*i.e.* antimony, nickel, or cerium). This approach improves the electronic conductivity and strengthens the tin-oxygen framework, thereby reducing the localized overpotential and slowing dissolution kinetics [93]. Oxidation and surface flaking are also inhibited by the introduction of intermediate barrier layers (*e.g*. titanium dioxide or antimony-doped interlayers), which suppress oxygen diffusion while enhancing surface adhesion, preventing the formation of insulating oxide layers. Surface passivation, caused by the accumulation of insulating reaction media, can be mitigated by nanotechnology materials, such as porous films and nanotubes. This method increases the electrochemically active surface area, enhances mass transfer efficiency, and preserves available

active sites during operation [94]. Furthermore, dopant leakage, a major factor in electrode degradation, can be reduced through co-grafting strategies (Sb-Ni or Sb-Ce) and improved heat treatment. These techniques enhance dopant incorporation into the crystal lattice and minimize dopant mobility under operating conditions [94]. Combining these strategies facilitates targeted control of the structure, interface, and shape of materials, enabling selective mitigation of various degradation mechanisms. This method underscores the importance of integrated material design to achieve long-term electrode stability.

Several researchers have proposed methods to increase the stability of SnO_2-based electrodes and to prevent the formation of passive layers externally. One method involves incorporating additive metal oxides into the SnO_2-Sb_2O_5 film to significantly increase the service lifetime of SnO_2-Sb_2O_5 anodes [94-96]. For example, adding IrO_x to a mixture of SnO_2-Sb_2O_5 increases the service lifetime of anodes, lasting 1600 h in 3 M H_2SO_4 solution at a current density of 1 A cm^{-2} [95]. Different metal oxides have been incorporated into Sb-doped SnO_2 anodes to increase their lifetime [62]. Adams *et al.* [62] employed thermal decomposition to fabricate four types of SnO_2-based anodes: Ti/SnO_2-Sb_2O_5, Ti/SnO_2-Sb_2O_5-IrO_2, Ti/SnO_2-Sb_2O_5-RuO_2, and Ti/SnO_2-Sb_2O_5-PtOx anodes. Among these electrodes, Ti/SnO_2-Sb_2O_5-IrO_2 demonstrated the longest service lifetime (155 days) at a current density of 160 mA cm^{-2} in 0.5 M NaOH solution. Correa-Lozano *et al*. [73] demonstrated that the existence of an IrO_2 film between the SnO_2-Sb_2O_5 layer and the Ti substrates can extend the electrode service lifetime. Coteiro *et al*. [97] investigated the effect of a solvent on the stability of a ternary oxide Ru-Ti-Sn electrode formed via thermal decomposition. The use of isopropanol as a solvent increased stability and eliminated tin loss.

Application of tin oxide anodes in wastewater treatment

For anodic oxidation-based wastewater treatment, three types of anodes have been utilized comprehensively: tin oxide groups, lead oxides and BDD. Each of these anodes has distinct performance-stability trade-offs [62,93,98]. The trade-offs among the SnO_2, PbO_2, and BDD anodes are summarized in Table 3.

Table 3. *Tradeoffs across SnO_2, PbO_2, and BDD anodes*

Property	BDD	Lead oxide	Tin oxide
Oxygen evolution overpotential	Very high (best option)	High	High with dopants
Rate of hydroxyl radicals generation	Extremely strong but nonselective	Strong	Strong
Mineralization efficiency	Very high	High	High
Selectivity	Very low	Moderate	Moderate
Electrical conductivity	Very high	Moderate	Moderate when doped with Sb or Nb
Service lifetime	Very long	Medium	Limited up to hundreds of hours
Environmental risk	Very low	High due to lead leaching	Low
Industrial scalability	Limited	Established but regulated	Promising

BDD is the best method, but it is costly and has limited scalability. Additionally, BDD suffers from several limitations, including carbon corrosion at high anodic potentials, microcrack formation, and surface fouling due to the adsorption of intermediates [99,100].

SnO_2 anodes are attractive because of their low cost, ease of scaling, and ability to generate physisorbed OH, which leads to high oxidation efficiency when handling refractory pollutants.

However, SnO_2 anodes suffer from Sn and dopant loss in addition to the formation of TiO_2 insulation in the case of Ti substrates [101]. Hence, the industrial application of SnO_2 anodes requires advanced materials engineering strategies to enhance interlayer design and dopant optimization. This review outlines the most recent applications of tin oxide anodes in wastewater treatment and their corresponding mechanisms.

In general, SnO_2-based anodes are used to treat various types of organic pollutants, including phenols, dyes, landfill leachate, and petroleum hydrocarbons. Table 4 presents the treatments of different pollutants *via* anodic oxidation using SnO_2-based anodes [62,96,102-121]. A comparison of the COD removal efficiencies under different operating conditions is also presented.

Table 4. *Performances of various types of SnO_2-based anode wastewater treatment via anodic oxidation*

Electrode material	Pollutants	Optimum conditions	Current density range, mA cm^{-2}	Removal efficiency, % COD	Energy consumption	Accelerated lifetime, h	Ref.
Binary oxide anodes							
Ti/Sb_2O_5-SnO_2	Dye: orangeII	750 mg L^{-1} orange II, 2 g L^{-1} Na_2SO_4, 6.25 Ah L^{-1}, 200 A m^{-2}, 30 °C	10 to 20	27	-	12 (1000 A m^{-2})	[102]
	Dye: reactive red HE-3B	Reactive red HE-3B (1,500 mg L^{-1}), COD (920 ppm) 2 g L^{-1} Na_2SO_4, 6.25 Ah L^{-1}, 200 A m^{-2}, 30 °C	10 to 20	22	-	-	[103]
	2-chlorophenol	COD (1000 ppm)2-chloro-phenol (400 to 600 mg L^{-1}) phosphoric solutions, flow rate 1 cm^3 s^{-1}, 25 °C, 16 mA cm^{-2}, time 500 min	8 to 16	70	-	-	[104]
	Glucose	1 g L^{-1} glucose1 M H_2SO_4, 90 mA cm^{-2}, 25 °C, time 24 h	37.5 to 90	30	-	-	[105]
	Phenol	1000 mg L^{-1}, 30 mA cm^{-2}, pH 12, 0.25 M Na_2SO_4, 8 Ah	-	100*	-	-	[106]
	Phenol	10 mM, 50 mA cm^{-2}, pH 12.5, 70 °C	-	71	-	-	[107]
	Cyanide	1 mmol L^{-1} KCN, 1 mol L^{-1} K_2SO_4, 4 mmol L^{-1} KCl, 25 °C; pH 12, 16 mA cm^{-2}	5 to 90	ND	-	44 (16 mA cm^{-2})	[108]
	Cypermethrin	50 mg L^{-1}, 80 mA cm^{-2}, *T* = 25 °C, pH 5.4	40 to 80	76	-	-	[109]
TiO_{2-x}NCs/ /Sb–SnO_2	Dye: rhodamine B methylene blue, methyl orange, alizarin yellow	20 mg L^{-1}, 10 g L^{-1} Na_2SO_4, 30 mA cm^{-2}, time 2 h, 40 °C	--	RhB - 78.2* MB - 67.6* MO - 63.4* AYR - 47.8*	1.9 kWh m^{-3} 9.3 kWh m^{-3} 19.2 kWh m^{-3} 6.1 kWh m^{-3}	23 (100 mA cm^{-2})	[110]
SnO_2-Sb_2O_3	Phenol	150 mg L^{-1} phenol, 3 g L^{-1} NaCl, *T* = 30 °C, pH 3; 25 mA cm^{-2}, 3 h	10 to 25	100	-	-	[111]
Ti/SnO_2-Sb	DOX	5 mg L^{-1} doxorubicin, 0.1 M Na_2SO_4, *T* = 25 °C, 7.7 mA cm^{-2}, 1 h	-	42*	1.128 kWh g_{TOC}^{-1}	-	[112]
Ti/SnO_2-RuO_2	Alizarin cyanin green(ACG)	150.0 mg L^{-1} ACG, 2 g NaCl, *T* = 25 °C, 3 mA cm^{-2}, time 40 min	1 to 4	51.3 80.4**	-	40 (500 mA cm^{-2})	[113]
Ternary oxide anodes							
$Ti/Ti_{0.5}Ru_{0.45}Sn_{0.05}O_2$	Landfill leachate	780 ppm COD, 266 mg L^{-1} NH_4Cl, flow rate 420 dm^3 h^{-1}, 40 mA cm^{-2}, time 8 h	-	35	150 kWh m^{-3}	-	[114]

Electrode material	Pollutants	Optimum conditions	Current density range, mA cm^{-2}	Removal efficiency, % COD	Energy consumption	Accelerated lifetime, h	Ref.
Ti/Sn-Pd-Ru oxide	Landfill leachate	4100 to 5000 ppm COD, 1000 ppm BOD, 266 ppm NH_4Cl, 2500 ppm chloride, 15 A dm^{-2}, 7,500 ppm chloride added, time 4 h	50 to 150	92	-	-	[115]
Ti/RuO_2-SnO_2-Sb_2O_5	Dye: reactive Black-5	100 mg L^{-1} reactive black-5, 2 g L^{-1}NaCl ,50 mA cm^{-2}, time 1 h, pH 2 to 3	-	55 98** 37*	0.35kWh mg_{COD}^{-1}	-	[116]
Ti/IrO_2-SnO_2-Sb_2O_5	Dye: indigo	1 mM indigo, flow rate 0.2 L min^{-1}, 0.05 M NaCl, 7 mA cm^{-2}), time 8 h	-	100	1.78 kWh m^{-3}	-	[117]
Ti/RuO_2-TiO_2-SnO_2	Petroleum hydrocarbons	15 g L^{-1} NaCl, 25-30 ppm benzene + toluene + ethyl benzene + xylene, 5 ppm phenol, 0.25 L h^{-1}, 89 mA cm^{-2}, time 2.3 h	-	98%	4.84 kWh m^{-3}	-	[118]
Ti/SnO_2-Sb_2O_3-PtO	Aniline	80 ppm aniline, 225 ppm COD, 10 g L^{-1} Na_2SO_4, pH 11, 15 mA cm^{-2}, 1 h	-	88.9	-	--	[96]
Ti/SnO_2-Sb_2O_5-IrO_2	2-Nitrophenol	0.05 to 0.275 mM2 -NPh, 0.5 M Na_2SO_4, 80 mA cm^{-2}, time 3 h, pH 2	16 to 120	70**	-----	155 days (160 mA cm^{-2})	[62]
Quaternary metal oxide anodes							
Ti/Ru-Ti-Sb-SnO_2 Pt/Ru-Ti-Sb-SnO_2	p-benzo-quinone	100 mg L^{-1}p-benzoquinone, 200 mA cm^{-2}, time 64 h	-	98.94	-	-	[119]
Ti/TiONTs/SnO-Sb-Bi/NATO	Dye: methy-lene blue (MB)	40 mg L^{-1} MB, time 30 min, T = 25 °C, 30 mA cm^{-2}	-	72.9 94.5**	-	37 min (1 A cm^{-2})	[120]
Ti/TiO_2-RNT_S/ /SnO_2-Sb-Ni-La	Oily wastewater	1 M H_2SO_4, T = 30 °C, pH 7, 10 mA cm^{-2}	-	72.02	-	-	[121]

*TOC, %; **colour, %; ND= No data

Regarding the oxidation of phenol and its derivatives, several studies have shown that Ti/SnO_2-Sb_2O_5 anodes exhibit superior oxidation performance compared with PbO_2, IrO_2, RuO_2, and Pt anodes. Kotz *et al*. [106] found that Ti/SnO_2-Sb_2O_5 anodes oxidized phenol fivefold more efficiently than Pt anodes. Comninellis [107] found that Ti/SnO_2-Sb_2O_5 has the highest phenol removal rate of 71 % compared with PbO_2, IrO_2, RuO_2 and Pt. Grimm *et al*. [122] found that Ti/SnO_2 achieved better phenol removal than PbO_2. Polcaro *et al*. [104] found that the Ti/SnO_2 electrode exhibited superior performance, achieving a 50% Faraday yield for 2-chlorophenol oxidation compared with the PbO_2 anode.

A common strategy for improving the performance of SnO_2 anodes involves incorporating catalysts or intermediate layers. Noble metal oxides, such as RuO_2, IrO_2 and PtOx, are introduced into SnO_2-Sb_2O_5 matrices to enhance electrode stability and catalytic activity. Adams *et al*. [62] found that the Ti/SnO_2-Sb_2O_5-IrO_2 electrode showed superior performance compared with the Ti/SnO_2-Sb_2O_5--RuO_2 and Ti/SnO_2-Sb_2O_5-PtOx electrodes during nitrophenol oxidation due to its long lifetime.

Tin oxide (SnO_2)-based anodes have been extensively studied in the oxidation of aromatic amines, such as aniline. Comparative experiments by Li *et al*. [96] using graphite, titanium/platinum, and modified SnO_2 electrodes demonstrated that SnO_2-doped materials can efficiently oxidize aniline. Fugivara *et al*. [108] showed that Ti/SnO_2-Sb_2O_3-PtO facilitates the conversion of intermediate compounds resulting from aniline oxidation (*i.e.* azobenzene derivatives and aniline phenols) to final mineralization products, such as carbon dioxide and water. These results demonstrate that modified SnO_2 anodes enhance the oxidation and mineralization pathways during electrochemical processing.

Anodic oxidation using SnO_2-based anodes has been successfully applied to treat landfill leachate containing high levels of organic pollutants and ammonium. Studies in this field have used various tin dioxide anodes, with tin, palladium, and ruthenium trioxide anodes regarded as the most effective materials for achieving high removal of COD and ammonium. Chiang *et al*. [115] used four types of anodes, namely, graphite, PbO_2/Ti, binary (Ru-Ti oxide-coated titanium), and ternary Sn-Pd-Ru (SPR) oxide-coated titanium, with the latter achieving the highest COD removal rate (92 %) and complete ammonium removal. In another study, three anodes (BDD, PbO_2, and a Ti-Ru-Sn ternary oxide [$TiRuSnO_2$]) were used, with the latter achieving 35 % removal of organic matter and 65 % removal of ammonium [114]. However, comparative studies have found that, despite the good performance of the SnO_2 anode, BDD anodes exhibit higher oxidation efficiency under certain operating conditions.

The electrochemical treatment of wastewater from the dye industry is another major application of tin oxide (SnO_2)-based electrodes. Ti/SnO_2-Sb anodes are promising materials for dye oxidation because they generate strong oxidizing species, thereby achieving significant decolorization and the required COD removal [96,123,124]. 2-Naphthol was degraded using BDD, PbO_2 and Ti-Ru-Sn ternary oxide anodes, with all anodes used to efficiently oxidize this material within the specified potential range under stable supporting electrolyte conditions [126-128]. However, studies comparing different anodes often show that BDD electrodes provide relatively high mineralization efficiency due to their high oxygen generation potential and ability to generate hydroxyl radicals [125]. In addition, the polymer films formed on the surface of tin oxide or BDD anodes during dye oxidation can contaminate these electrodes and limit their long-term performance.

Recent studies have focused on improving tin oxide (SnO_2) electrodes *via* advanced structural design. The introduction of intermediate layers of titanium dioxide (TiO_2) nanoclustered assemblies, addition of dopants (niobium oxide (Nb_2O_5), or bismuth-containing oxides), and electrode morphology improvements have significantly enhanced electrode performance [110,113,120,129-132]. These modifications promote OH generation, reduce charge-transfer resistance, and extend electrode lifetime. In certain cases, these strategies have resulted in several times the electrode lifetime compared with conventional SnO_2 electrodes.

Tin oxide (SnO_2)-based anodes have been successfully used to treat petroleum hydrocarbons and petrochemical wastewater [118,119]. Studies indicate that electrode structure, operating parameters, and hydrodynamic conditions significantly affect treatment efficiency. Advanced self-assembling tin oxide (SnO_2)-based anodes have demonstrated high oil-removal efficiency and significantly higher degradation rate constants than conventional electrodes [130]. Zhao *et al*. [130] used a highly active titanium/tin oxide-antimony (Ti/TiO_2-RNTS/SnO_2-Sb-Ni-La) self-assembled anode for petrochemical waste treatment. This anode features a dense structure, a high oxygen potential (2.17 V), and a low charge transfer resistance (5.36 Ω). Improving these properties resulted in an oil removal rate of 97.88 % under optimal conditions. Compared with conventional tin oxide electrodes, the degradation rate constant of this anode increased by a factor of 2.67, and the electrode's service life increased by a factor of 8.60. Furthermore, the use of pulsed-current electrochemical oxidation reduced electrical power consumption, thereby improving process efficiency.

Many researchers have studied the treatment of wastewater from petroleum refining processes and have demonstrated the good performance of tin oxide anodes. Recently, Al-Tamimi *et al.* [131] used an innovative design prepared *via* cathodic deposition, which is characterized by its ease of scale. The prepared electrode reduced COD with a removal efficiency of 79 % and decreased energy consumption.

In general, tin oxide (SnO_2)-based anodes have strong potential to be used for the electrochemical oxidation of a wide range of organic pollutants, including phenols, dyes, petrochemicals, oil refinery pollutants, and leachate from landfills. Their oxidation ability is significantly influenced by electrode composition, structural modifications, and operating conditions. Key design principles derived from published work include selecting the appropriate dopant, optimizing the electrode shape, and controlling electrochemical parameters to maximize oxidation efficiency while maintaining electrode stability.

Challenges, improvement, and future application of SnO_2-based electrodes

SnO_2-based anodes offer multiple advantages, but their relatively short service life and instability limit their industrial applications. Many researchers have attempted to improve the service life and catalytic efficiency of these anodes through modification techniques, such as doping or structural changes, to increase the bonding strength between the substrates and the surface-active layers.

Modification by doping

Doping SnO_2-based anodes with different elements improves their electrocatalytic activity [5]. The doping elements used for modification include rare-earth metals (Ce, La, Nd, Eu, and Dy) [133-135], precious metals (Pt, Ru, and Ir) [136,137], and iron-group metals (Fe, Co, and Ni) [136,138]. Zhu *et al*. [134] reported that adding Ce, La, Eu and Dy improves the catalytic activity of anodes, resulting in the highest oxygen evolution potential and longest surface life for Ti/SnO_2-Sb-La. Li *et al.* [135] reported that adding Pd increases the service lifetime by more than 40-fold compared with that of Ti/SnO_2-Sb. Yang *et al*. [136] reported that modifying Ti/SnO_2-Sb with Fe and Ni enhances the anodes' electrocatalytic activity in degrading phenol. Berenguer *et al*. [137] studied the effects of adding Pt and Ru onto Ti/SnO_2-Sb and compared them with those of Ti/RuO_2. The addition of Pt resulted in the best electroactivity and high current efficiency, whereas the addition of Ru led to a remarkable increase in stability.

Structure modification

Methods for modifying the structure of SnO_2-based anodes include active-layer modification and intermediate-layer structural modification. The first method is achieved by changing the preparation of the SnO_2 layer, and the second by adding an intermediate layer to enhance the binding between the substrate and the active layer [4,138]. Wang *et al*. [139] prepared SnO_2-based anodes with 3D hierarchical flower-like structures. Compared with traditional SnO_2 anodes, this modification resulted in a larger active surface area, lower charge-transfer resistance, and a higher oxygen evolution potential.

Recent studies have focused on the preparation of nanostructured SnO_2-based anodes, such as nanorods, nanotubes, and honeycombs, to increase mass transfer rates and surface areas. An ordered-stack microstructure of SnO_2/TiO_2 nanotubes was fabricated by combining anodic oxidation to construct TiO2 nanotubes with a modified surfactant-assisted sol-gel method to develop a tin oxide microstructure [140,141]. This type of electrode resulted in excellent electrocatalytic and photothermal activities owing to the strong bonding between the SnO_2 layer and the Ti substrate. Another type of SnO_2-based anode with excellent oxidation capability is a sieve-like macroporous Sb-SnO_2/TiO_2NTs prepared via a block copolymer-based soft-template technique [141,142]. Compared with traditional anodes, the proposed anode has a larger electrochemical surface area, lower reaction activation energy, and lower electrochemical impedance [141,142]. Given the excellent properties of nanostructured tin oxide anodes, further studies should be conducted to

optimize preparation methods. The goal is to develop advanced electrochemical oxidation approaches that use tin oxide anodes as the sample material.

A comprehensive evaluation of anode technologies should consider electrochemical performance, capital and operating costs, environmental risks, and scalability. Tin oxide (SnO_2)-based anodes offer competitive material and manufacturing costs (typically 25 to 300 US$ *per* m²) compared to current DSA electrodes (approximately 3,000 US$ *per* m^2), but their stability issues necessitate frequent replacement, increasing their lifecycle cost [143]. Lead oxide (PbO_2) anodes are relatively cost-effective and have high oxidizing capacity, but the risk of lead ion (Pb^{2+}) leakage and associated regulatory restrictions complicate their industrial use. BDD anodes offer unparalleled durability and minimal additive leakage, but their high manufacturing cost (typically 5,000 to 25,000 US$ *per* m^2) and the need for specialized fabrication infrastructures limit scalability; however, they are suitable for high-value wastewater treatment applications [144]. The durability of the electrodes is a critical factor in the industrial adoption of tin oxide anodes, as degradation affects operating costs and process reliability. Accelerating the lifetime of Ti/SnO_2 anodes typically ranges from 10 to 1000 h; by contrast, BDD anodes have a lifetime of up to 5000 h. Improving the durability of tin oxide anodes is a top research priority and can be enhanced through doping or structural modification. However, the use of tin oxide anodes raises environmental concerns due to the leaching of antimony and doping elements during operation, with antimony not to exceed 0.2 mg L^{-1} [145]. Long-term operation requires post-treatment or monitoring of metal concentrations. Energy consumption is another important factor in the industrial feasibility of using tin oxide anodes. Studies indicate that the energy consumption of anodic oxidation treatment ranges from 5 to 80 kWh m^{-3}, which is higher than that of electro-Fenton or ozonation processes [145]. Reducing this energy by improving mass transfer and current efficiency is a successful strategy for the industrial adoption of SnO_2 anodes. Additionally, the factors affecting different manufacturing methods must be studied to address the limitations of using tin oxide anodes. These factors include low current efficiency, short service life, anode material flaking, and the risk of chlorinated byproduct formation. Addressing these limitations will allow for the gradual adoption of tin oxide anodes in industrial applications.

Conclusions

Electrochemical oxidation has emerged as a promising approach for addressing a wide range of environmental pollution issues, particularly wastewater treatment. SnO_2-based anodes are equipped to degrade organic pollutants in wastewater, and their high oxidative capacity and dimensional stability have been confirmed. However, the use of SnO_2-based electrodes in wastewater treatment requires the optimization of operational parameters, such as current density, pH, electrolyte composition, and chloride addition, prior to achieving optimal performance. SnO_2-Sb electrodes are typically fabricated on titanium substrates, where various surface preparation techniques improve adhesion and performance. Substrate properties and different fabrication methods, including the sol-gel method, influence layer structures and longevity. Many studies have confirmed improved performance of doped SnO_2 anodes as hydroxyl (OH-) generation increases. Despite these excellent results, several challenges remain. In general, issues related to deactivation mechanisms and long-term stability have limited the industrial application of the aforementioned anodes. Dopant leaching and surface passivation also require further investigation. Energy consumption remains a major obstacle in economic evaluation, particularly in the treatment of wastewater with high COD. Many studies have proposed novel doping methods to enhance the electrochemical stability of anodes. A promising strategy involves combining titanium dioxide

nanotubes with SnO_2 catalysts to produce microstructured titanium dioxide-based anodes with exceptional stability and oxidation capacity. However, further research is needed to improve the preparation methods for tin oxide anodes. In addition to improving the anode material, cell design to optimize anodic oxidation in tin oxide-based anodes should be considered. Most studies have relied on nonpartitioned cell designs despite several drawbacks, such as reduced overall efficiency due to competing species at the anodes, which hinder the reduction reaction at the cathode. A two-chamber cell design offers promising performance, and further research in this direction is recommended. Exploring the design of a hybrid reactor by combining anodic oxidation with electro-Fenton, photo-Fenton, photocatalysis, and membrane separation can also significantly improve removal efficiency and reduce energy consumption. Integrating anodic oxidation with renewable energy systems, such as photovoltaic cells, represents a promising path toward sustainable operation, particularly in regions with abundant renewable energy sources.

Another area for further research is the development of new manufacturing and modification methods. Currently, most synthesis processes are based on sol–gel reactions, which require multiple repetitions to achieve layers with reasonable coverage. Simple chemical synthesis routes might reduce the cost of the final electrode materials while improving performance in wastewater treatment.

The results of this review showed that tin oxide (SnO_2)-based anodes are a viable alternative for wastewater treatment via anodic oxidation, provided that moderate current density, low capital cost, and the potential for large-scale electrode fabrication are identified as key operational priorities. Tin oxide anodes are attractive for treating large volumes of wastewater, where the ease of electrode fabrication and economic considerations outweigh the high power requirements for oxidation. In these cases, tin oxide anodes provide adequate contaminant removal within acceptable ranges of material and energy costs.

However, with respect to high mineralization efficiency with long-term stability, BDD is preferable because of its wide potential range, indicating high hydroxyl radical (•OH) generation. However, these advantages are limited by BDD's high manufacturing cost and the complexity of its steps. Overall, the choice between tin oxide and BDD should be guided by a balance between economic feasibility and high oxidation requirements. The treatment objectives and operating-condition constraints for the target wastewater are also important considerations.

SnO_2 electrodes are suitable for use as industrial anodes, as they can be used in applications requiring high oxidation capacity at a reasonable cost, provided appropriate material design strategies are employed to mitigate dissolution, passivation, and interfacial degradation.

***Acknowledgments**: The authors would like to thank the technical staff of the Department of Biochemical Engineering, Al-Khwarizmi College, University of Baghdad, for their assistance and support.*

***Funding:** No funding*

References

[1] M. E. H. Bergmann, A. S. Koparal, T. Iourtchouk, Electrochemical Advanced Oxidation Processes, Formation of Halogenate and Perhalogenate Species: A Critical Review, *Critical Review Environment Science and Technology* **44** (2014) 348390. https://doi.org/10.1080/10643389.2012.718948

[2] M. Jiad, A. Abbar, Treatment of petroleum refinery wastewater by electrofenton process using a low cost porous graphite air-diffusion cathode with a novel design, *Chemical Engineering Research and Design* **193** (2023) 207-221. https://doi.org/10.1016/j.cherd.2023.03.021

[3] M. Jiad, A. Abbar, Treatment of petroleum refinery wastewater by an innovative electro-Fenton system: Performance and specific energy consumption evaluation, *Case Studies in*

Chemical and Environmental Engineering **8** (2023) 100431. https://doi.org/10.1016/j.cscee.2023.100431

[4] F. Cao, J. Tan, S. Zhang, H. Wang, C. Yao, Y. Li, Preparation and Recent Developments of Ti/SnO_2-Sb Electrodes, *Journal of Chemistry* **2021** (2021) 2107939. https://doi.org/10.1155/2021/2107939

[5] M. Gattrell, D. W. Kirk, The electrochemical oxidation of aqueous phenol at a glassy carbon electrode, *The Canadian Journal of Chemical Engineering* **68** (1990) 997-1003. https://doi.org/10.1002/cjce.5450680615

[6] X. Li, Y. Cui, Y. Feng, Z. Xie, J. Gu, Reaction pathways and mechanisms of the electrochemical degradation of phenol on different electrodes, *Water Research* **29** (2005) 1972-1981. https://doi.org/10.1016/j.watres.2005.02.021

[7] L. Szpyrkowicz, J. Naumczyk, F. Zilio-Grandi, Electrochemical treatment of tannery wastewater using TiPt and Ti/Pt/Ir electrodes, *Water Research* **29** (1995) 517-524. https://doi.org/10.1016/0043-1354(94)00176-8

[8] L. Szpyrkowicz, J. Naumczyk, F. Zilio-Grandi, Application of electrochemical processes for tannery wastewater treatment, *Toxicological & Environmental Chemistry* **44** (1994) 189-202. https://doi.org/10.1080/02772249409358057

[9] N. N. Rao, K. M. Somasekhar, S. N. Kaul, L. Szpyrkowicz, Electrochemical oxidation of tannery wastewater, *Journal of Chemical Technology and Biotechnology* **76** (2001) 1124-1131. https://doi.org/10.1002/jctb.493

[10] J. Boudenne, O. Cerclier, J. Galéa, E. V. D. Vlist, Electrochemical oxidation of aqueous phenol at a carbon black slurry electrode, *Applied Catalysis A: General* **143** (1996) 185-20243. https://doi.org/10.1016/0926-860X(96)00027-0

[11] A. Polcaro, S. Palmas, Electrochemical oxidation of chlorophenols, *Industrial & Engineering Chemistry Research* **36** (1997) 1791-1798. https://doi.org/10.1021/ie960557g

[12] N. S. Abuzaid, Z. Al-Hamouz, A. A. Bukhari, M. H. Essa, Electrochemical treatment of nitrite using stainless steel electrodes, *Water, Air, Soil Pollution* **109** (1999) 429-442. https://doi.org/10.1023/A:1005024012610

[13] J. Manriquez , J. L. Bravo, S. Gutierrez-Granados, S. Succar, C. B. Chariton, A. Alatorre Ordaz, F. Bedioui, Electrocatalysis of the oxidation of alcohol and phenol derivative pollutants at vitreous carbon electrode coated by nickel macrocyclic complex-based films, *Analytica Chimica Acta* **378** (1999) 159-168. https://doi.org/10.1016/S0003-2670(98)00564-9

[14] P. Britto-Costa, L.A. M. Ruotolo, Phenol removal from wastewaters by electrochemical oxidation using boron doped diamond (BDD) and Ti/$Ti_{0.7}Ru_{0.3}O_2$ DSA electrodes, *Brazilian Journal of Chemical Engineering* **29** (2014) 763-773. https://doi.org/10.1590/S0104-66322012000400008

[15] N. Mameda, H. Park, S. S. Ali Shah, K. Lee, C. Li, V. Naddeo, K. Choo, Highly robust and efficient Ti-based Sb-SnO_2 anode with a mixed carbon and nitrogen interlayer for electrochemical 1,4-dioxane removal from water, *Chemical Engineering Journal* **393** (2020) 124794. https://doi.org/10.1016/j.cej.2020.124794

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

[17] A. Y. Bagastyo, A. D. Anggrainy, B. Rosyidah, The Role of Boron-Doped Diamond and Platinum Anodes in the Three-Compartment Electrochemical Pretreatment of Stabilized Landfill Leachate - Response Surface Methodological Approach, *Journal of Ecological Engineering* **12** (2022) 50-60. https://doi.org/10.12911/22998993/154980

[18] W. Wu, Z. Huang, T.L.-A.C.A. General, Recent development of mixed metal oxide anodes for electrochemical oxidation of organic pollutants in water, *Applied Catalysis A: General* **480** (2014) 58-78. https://doi.org/10.1016/j.apcata.2014.04.035

[19] K. Jüttner, U. Galla, H. Schmieder, Electrochemical approaches to environmental problems in the process industry, *Electrochimica Acta* **45** (2000) 2575-2594. https://doi.org/10.1016/S0013-4686(00)00339-X

[20] H. Lin, J. Niu, S. Ding, L. Zang, Electrochemical degradation of perfluorooctanoic acid (PFOA) by Ti/SnO_2-Sb, Ti/SnO_2-Sb/PbO_2 and Ti/SnO_2-Sb/MnO_2, *Water Research* **46** (2012) 2281-2289. https://doi.org/10.1016/j.watres.2012.01.053

[21] J. Radjenovic, B.I. Escher, K. Rabaey, Electrochemical degradation of the β-blocker metoprolol by Ti/$Ru_{0.7}Ir_{0.3}O_2$ and Ti/SnO_2-Sb electrodes, *Water Research* **45** (2011) 3205-3214. https://doi.org/10.1016/j.watres.2011.03.040

[22] Y. Jiang, H. Zhao, J. Liang, L. Yue, T. Li, Y. Luo, Q. Liu, S. Lu, A. Asiri, Z. Gong, X. Sun, Anodic oxidation for the degradation of organic pollutants: anode materials, operating conditions and mechanisms. A mini review, *Electrochemistry Communications* **123** (2021) 106912. https://doi.org/10.1016/j.elecom.2020.106912

[23] N. Oturan, E. D. V. Hullebusch, H. Zhang, L. Mazeas, H. Budzinski, K. L. Menach, M. A. Oturan, Occurrence and removal of organic micropollutants in landfill leachates treated by electrochemical advanced oxidation processes, *Environmental Science and Technology* **49** (2015) 12187-12196. https://doi.org/10.1021/ACS.EST.5B02809

[24] S. Asim, Y. Zhu, A. Batool, R. Hailili, J. Luo, Y. Wang, C. Wang, Electrochemical treatment of 2, 4-dichlorophenol using a nanostructured 3D-porous Ti/Sb-SnO_2-Gr anode: Reaction kinetics, mechanism, and continuous operation, *Chemosphere* **185** (2017) 11-19. https://doi.org/10.1016/j.chemosphere.2017.06.125

[25] X. Li, H. Xu, W. Yan, D. Shao, Electrocatalytic degradation of aniline by Ti/Sb-SnO_2, Ti/Sb-SnO_2/Pb_3O_4 and Ti/Sb-SnO_2/PbO_2 anodes in different electrolytes, *Journal of Electro-analytical Chemistry* **775** (2016) 43-51. https://doi.org/10.1016/j.jelechem.2016.05.033

[26] C. Zhou, Y. Wang, J. Chen, J. Niu, Electrochemical degradation of sunscreen agent benzophenone-3 and its metabolite by Ti/SnO_2-Sb/Ce-PbO_2 anode: kinetics, mechanism, toxicity and energy consumption, *Science of The Total Environment* **688** (2019) 75-82. https://doi.org/10.1016/j.scitotenv.2019.06.197

[27] I. Sirés, N. Oturan, M. A. Oturan, Electrochemical degradation of β-blockers. Studies on single and multicomponent synthetic aqueous solutions, *Water Research* **44** (2010) 3109-3120. https://doi.org/10.1016/j.watres.2010.03.005

[28] Y. Cao, S. Ge, X. M. Xu, X. Zhou, Application of the synergistic Ti/SnO_2-Sb-Cu anode and Ti/ZnO/CuO cathode in the electrochemical treatment of wastewater, *Materials Science in Semiconductor Processing* **172** (2024) 108097. https://doi.org/10.1016/j.mssp.2023.108097

[29] C. García-Gómez, P. Drogui, F. Zaviska, B. Seyhi, P. Gortáres, G. Buelna, C. Neira, M. Estrada, R.G. Mercado, Experimental design methodology applied to electrochemical oxidation of carbamazepine using Ti/PbO_2 and Ti/BDD electrodes, *Journal of Electroanalytical Chemistry* **732** (2014) 1-10. https://doi.org/10.1016/j.jelechem.2014.08.032

[30] J. Li, M. Li, D. Li, Q. Wen, Z. Chen, Electrochemical pretreatment of coal gasification wastewater with Bi-doped PbO_2 electrode: preparation of anode, efficiency and mechanism, *Chemosphere* **248** (2020) 126021. https://doi.org/10.1016/j.chemosphere.2020.126021

[31] F.H. Abd, A. Abbar, Treatment of hospital wastewater by anodic oxidation using a new approach made by combining rotation with pulsed electric current on Cu-SnO_2-Sb_2O_5 rotating cylinder anode, *Heliyon* **11** (2025) e42069. https://doi.org/10.1016/j.heliyon.2025.e42069

[32] X. Duan, F. Xu, Y. Wang, Y. Chen, L. Cheng, Fabrication of a hydrophobic SDBS-PbO_2 anode for electrochemical degradation of nitrobenzene in aqueous solution, *Electrochimica Acta* **282** (2018) 662-671. https://doi.org/10.1016/j.electacta.2018.06.098

[33] C. Rajkumar, P. Veerakumar, S.-M. Chen, B. Thirumalraj, K.C. Lin, Ultrathin sulfur-doped graphitic carbon nitride nanosheets as metal-free catalyst for electrochemical sensing and catalytic removal of 4-nitrophenol, *ACS Sustainable Chemistry and Engineering* **6** (2018) 16021-16031. https://doi.org/10.1021/ACSSUSCHEMENG.8B02041

[34] M. Panizza, A. Barbucci, R. Ricotti, G. Cerisola, Electrochemical degradation of methylene blue, *Separation and Purification Technology* **54** (2007) 382-387. https://doi.org/10.1016/j.seppur.2006.10.010

[35] U. Un, U. Altay, A. Koparal, U. Ogutveren, Complete treatment of olive mill wastewaters by electrooxidation, *Chemical Engineering Journal* **139** (2008) 445-452. https://doi.org/10.1016/j.cej.2007.08.009

[36] S. C. Perry, C. P. De León, F. C. Walsh, The design, performance and continuing development of electrochemical reactors for clean electrosynthesis, *Journal of The Electrochemical Society* **167** (2020) 155525. https://doi.org/10.1149/1945-7111/abc58e

[37] J. Liu, N. Ren, C. Qu, S. Lu, Y. Xiang, D. Liang, Recent advances in the reactor design for industrial wastewater treatment by electro-oxidation process, *Water* **14** (2022) 3711. https://doi.org/10.3390/w14223711

[38] H. Monteil, Y. Pechaud, N. Oturan, C. Trellu, M. A. Oturan, Pilot scale continuous reactor for water treatment by electrochemical advanced oxidation processes: Development of a new hydrodynamic/reactive combined model, *Chemical Engineering Journal* **404** (2021) 127048. https://doi.org/10.1016/j.cej.2020.127048

[39] Á. F. Ferrer, I. Tudela, O. Louisnard, V. Sáez, M. D. Esclapez, M. I. D. García, P. Bonete, J. G. García, Optimized design of an electrochemical filter-press reactor using CFD methods, *Chemical Engineering Journal* **169** (2011) 270-281. https://doi.org/10.1016/j.cej.2011.02.053

[40] A. Regalado-Méndez, J. Mentado-Morales, C. E. Vázquez, G. Martinez-Villa, M. E. Cordero, L.G. Zárate, S. Skogestad, E. Peralta-Reyes, Modeling and hydraulic characterization of a filter-press-type electrochemical reactor by using residence time distribution analysis and hydraulic indices, *International Journal of Chemical Reactor Engineering* **16** (2018). https://doi.org/10.1515/ijcre-2017-0210

[41] B. Körbahti, A. Tanyolac, Electrochemical treatment of simulated industrial paint wastewater in a continuous tubular reactor, *Chemical Engineering Journal* **148** (2009) 444-451. https://doi.org/10.1016/j.cej.2008.09.019

[42] D. Skban Ibrahim, P. Seethala Devi, C. Veerababhu, N. Balasubramanian, Treatment of petroleum effluent using a tubular electrochemical reactor, *Petroleum Science and Technology* **32** (2014) 1932-1939. https://doi.org/10.1080/10916466.2012.701693

[43] D. Li, J. Tang, X. Zhou, J. Li, X. Sun, J. Shen, L. Wang, H. Wang, Electrochemical degradation of pyridine by Ti/SnO_2-Sb tubular porous electrode, *Chemosphere* **149** (2016) 49-56. https://doi.org/10.1016/j.chemosphere.2016.01.078

[44] N. Nippatla, L. Philip, Performance evaluation of a novel electrolytic reactor with rotating and non rotating bipolar disc electrodes for synthetic textile wastewater treatment, *Journal of Environmental Chemical Engineering* **8** (2022) 103462. https://doi.org/10.1016/j.jece.2019.103462

[45] M. S. Kothari, A.A. Hassan, K. A. Shab, Three-dimensional electrochemical oxidation of recalcitrant dye using green iron microparticles, *Water* **13** (2014) 1925. https://doi.org/10.3390/w13141925

[46] J. Ni, H. Shi, Y. Xu, Q. Wang, A comparison of the mechanism of TOC and COD gradation in rhodamine B wastewater by a recycling-flow two-and three-dimensional electro-reactor, *Water* **12** (2020) 1853. https://doi.org/10.3390/w12071853

[47] Z. M. Jarzebski, J. P. Marton, Physical properties of SnO_2 materials: I. preparation and defect structure, *Journal of The Electrochemical Society* **123** (1976) 199C-205C. https://doi.org/10.1149/1.2133010
[48] M. Batzill, U. Diebold, The surface and materials science of tin oxide, *Progress in Surface Science* **79** (2005) 47-154. https://doi.org/10.1016/j.progsurf.2005.09.002
[49] G. J. A. Mannie, *Surface chemistry and morphology of tin oxide thin films grown by chemical vapor deposition,* PhD Thesis, Technische Universiteit Eindhoven, The Netherlands, 2013. https://doi.org/10.6100/IR751861
[50] Ç. Kılıç, A. Zunger, Origins of Coexistence of Conductivity and Transparency in SnO_2, P*hysical Review Letters* **88** (2002) 955011-955014. https://doi.org/10.1103/PHYSREVLETT.88.095501
[51] C. M. Huitle, S. Ferro, Electrochemical oxidation of organic pollutants for the wastewater treatment: direct and indirect processes, *Chemical Society Review* **35** (2006) 1324-1340. https://doi.org/10.1039/B517632H
[52] Y. Hsu, S. Ghandhi, The Effect of Phosphorus Doping on Tin Oxide Films Made by the Oxidation of Phosphine and Tetramethyltin: II. Electrical Properties, *Journal of The Electrochemical Society* **127** (1980) 1595-1599. https://doi.org/10.1149/1.2129959
[53] Y. Hsu, S. Ghandhi, The Effect of Phosphorus Doping on Tin Oxide Films Made by the Oxidation of Phosphine and Tetramethyltin: I. Growth and Etching Properties, *Journal of The Electrochemical Society* **127** (1980) 1592-1595. https://doi.org/10.1149/1.2129958
[54] Y. Hsu, S. Ghandhi, The Preparation and Properties of Arsenic-Doped Tin Oxide, *Journal of The Electrochemical Society* **126** (1979) 1434-1435. https://doi.org/10.1149/1.2130539
[55] C. Vincent, D. Weston, Preparation and properties of semiconducting polycrystalline tin oxide, *Journal of The Electrochemical Society* **119** (1972) 58. https://doi.org/10.1149/1.2404242
[56] C. Comninellis, C. Pulgarin, Electrochemical oxidation of phenol for wastewater treatment using SnO_2 anodes, *Journal of Applied Electrochemistry* **23** (1993) 108-112. https://doi.org/10.1007/bf00246946
[57] F. Vicent, E. Morallón, C. Quijada, J. L. Vázquez, A. Aldaz, F. Cases, Characterization and stability of doped SnO_2 anodes, *Journal of Applied Electrochemistry* **28** (1998) 607-612. https://doi.org/10.1023/A:1003250118996
[58] G. Chen, Electrochemical technologies in wastewater treatment, *Separation and Purification Technology* **38** (2004) 11-41. https://doi.org/10.1016/j.seppur.2003.10.006
[59] M. Panizza, G. Cerisola, Direct and mediated anodic oxidation of organic pollutants, *Chemical Reviews* **109** (2009) 6541-6569. https://doi.org/10.1021/cr9001319
[60] G. Zhao, X. Cui, M. Liu, P. Li, Y. Zhang, T. Cao ,H. Li, Y. Lei,L. Liu, D. Li, Electrochemical degradation of refractory pollutant using a novel microstructured TiO_2 nanotubes/Sb-doped SnO_2 electrode, *Environmental Science & Technology* **43** (2009)1480-1486. https://doi.org/10.1021/es802155p
[61] B. C. Lozano, C. Comninellis, A. D. Battisti, Service life of Ti/SnO_2-Sb_2O_5 anodes, *Journal of Applied Electrochemistry* **27** (1997) 970-974. https://doi.org/10.1023/A:1018414005000
[62] B. Adams, M. Tian, A. Chen, Design and electrochemical study of SnO_2-based mixed oxide electrodes, *Electrochimica Acta* **54** (2009) 1491-1498. https://doi.org/10.1016/j.electacta.2008.09.034
[63] P. Yao, X. Chen, H. Wu, D. Wang, Active Ti/SnO_2 anodes for pollutants oxidation prepared using chemical vapor deposition, *Surface and Coatings Technology* **202** (2008) 3850-3855. https://doi.org/10.1016/j.surfcoat.2008.01.026

[64] J. Scott, R. Martinez-Gazoni, M. W. Allen, R. J. Reeves, Optical and electronic properties of high quality Sb-doped SnO_2 thin films grown by mist chemical vapor deposition, *Journal of Applied Physics* **126** (2019) 135702. https://doi.org/10.1063/1.5116719
[65] Y. Liu, M. Liu, Growth of Aligned Square-Shaped SnO_2 Tube Arrays, *Advanced Functional Materials* **15** (2005) 57-62. https://doi.org/10.1002/adfm.200400001
[66] N. A. D. Ho, H. L. Duong, B. Van Nhat, N. H. Dan, N. C. Thuan, T. B. Son, J. Hoinkis, T. Le Luu, SnO_2-Mixed Oxide Electrodes for Water Treatment: Role of the Low-Cost Active Anode, *Cost-Efficient Wastewater Treatment Technologies* **118** (2023) 255-284. https://doi.org/10.1007/698_2022_874
[67] W. Wang, C. Xu, G. Wang, Y. Liu, C. Zheng, Synthesis and Raman scattering study of rutile nanowires, *Journal of Applied Physics* **92** (2002) 2740-2742. https://doi.org/10.1063/1.1497718
[68] J. Chatelon, C. Terrier, E. Bernstein, R. Berjoan, J. A Roger, Morphology of SnO_2 thin films obtained by the sol-gel technique, *Thin Solid Films* **247** (1994) 162-168. https://doi.org/10.1016/0040-6090(94)90794-3
[69] M. Seo, Y. Akutsu, H. Kagemoto, Preparation and properties of Sb-doped SnO /metal substrates by sol-gel and dip coating, *Ceramics International* **33** (2007) 625-629. https://doi.org/10.1016/j.ceramint.2005.11.013
[70] G. Zhang, M. Liu, Preparation of nanostructured tin oxide using a sol-gel process based on tin tetrachloride and ethylene glycol, *Journal of Materials Science* **34** (1999) 3213-3219. https://doi.org/10.1023/A:1004685907751
[71] S. V. Manorama, C.V. Gopal Reddy, V. J. Rao, Tin dioxide nanoparticles prepared by sol-gel method for an improved hydrogen sulfide sensor, *Nanostructured Materials* **11** (1999) 643-649. https://doi.org/10.1016/S0965-9773(99)00352-9
[72] J. Huang, N. Matsunaga, K. Shimanoe, N. Yamazoe, T. Kunitake, Nanotubular SnO_2 Templated by Cellulose Fibers: Synthesis and Gas Sensing, *Chemistry of Materials* **17** (2005) 3513-3518. https://doi.org/10.1021/cm047819m
[73] B. Correa-Lozano, C. Comninellis, A. De Battisti, Physicochemical Properties of SnO_2 - Sb_2O_5 Films Prepared by the Spray Pyrolysis Technique, *Journal of The Electrochemical Society* **143** (1996) 203-209. https://doi.org/10.1149/1.1836409
[74] G. E. Patil, D. D. Kajale, V. B. Gaikwad, G. H. Jain, Spray Pyrolysis Deposition of Nanostructured Tin Oxide Thin Films, in: *International Scholarly Research Notices*, Wiley Online Library, 2012, 275872. https://doi.org/10.5402/2012/275872
[75] B. Ong, H. Lee, Sh. Abdul Hamid, Morphological and Structural Study of Nanostructured Tin Dioxide (SnO_2) Thin Films by Spray Pyrolysis, *Advanced Materials Research* **626** (2012) 672-676. https://doi.org/10.4028/www.scientific.net/AMR.626.672
[76] S. Deng, Y. Dai, Y. Situ, D. Liu, H. Huang, Preparation of nanosheet-based spherical Ti/SnO_2-Sb electrode by in-situ hydrothermal method and its performance in the degradation of methylene blue, *Electrochimica Acta* **398** (2021) 139335. https://doi.org/10.1016/j.electacta.2021.139335
[77] S. Man, X. Zeng, Z. Yin, H. Yang, H. Bao, K. Xu, L. Wang, X. Ge, Z. Mo, W. Yang, X. Li, Preparation of a novel Ce and Sb co-doped SnO_2 nanoflowers electrode by a two-step (hydrothermal and thermal decomposition) method for organic pollutants electrochemical degradation, *Electrochimica Acta* **411** (2022) 140066. https://doi.org/10.1016/j.electacta.2022.140066
[78] E. Giani, R. Kelly, A Study of SnO_2 Thin Films Formed by Sputtering and by Anodizing, *Journal of The Electrochemical Society* **121** (1974) 121-394. https://doi.org/10.1149/1.2401823
[79] Md. Hossain, G. Yang, M. Parameswaran, J.R. Jennings, Q. Wang, Mesoporous SnO_2 Spheres Synthesized by Electrochemical Anodization and Their Application in CdSe-

Sensitized Solar Cells, *The Journal of Physical Chemistry C* **114** (2010) 21878-21884. https://doi.org/10.1021/jp109083k

[80] A. Yamaguchi, T. Iimura, K. Hotta, N. Teramae, Transparent nanoporous tin-oxide film electrode fabricated by anodization, *Thin Solid Films* **519** (2011) 2415-2420. https://doi.org/10.1016/j.tsf.2010.11.049

[81] H. Le Minh, Electrodeposition of nanostructured SnO_2 films for DNA label-free electrochemical detection, PhD thesis, Université de Grenoble; Institut Polytechnique (Hanoï), 2015. https://doi.org/tel-01204836

[82] J. Xiong, C. Han, Z. Li, S. Dou, Effects of nanostructure on clean energy: big solutions gained from small features, *Science Bulletin* **60** (2015) 2083-2090. https://doi.org/10.1007/s11434-015-0972-z

[83] S. T. Chang, I. C. Leu, M. H. Hon, Preparation and Characterization of Nanostructured Tin Oxide Films by Electrochemical Deposition, *Electrochemical and Solid-State Letters* **5** (2002) D1. https://doi.org/10.1149/1.1485808

[84] S. T. Chang, I. C. Leu, M. H. Hon, Electrodeposition of nanocrystalline SnO_2 coatings with two-layer microstructure, *Journal of Crystal Growth* **273** (2004) 195-202. https://doi.org/10.1016/j.jcrysgro.2004.07.087

[85] X. Chen, J. Liang, Z. Zhou, H. Duan, B. Li, Q. Yang, The preparation of SnO_2 film by electrodeposition, *Materials Research Bulletin* **45** (2010) 2006-2011. https://doi.org/10.1016/j.materresbull.2010.07.029

[86] S. Kim, H. Lee, Ch. M. Park, Y. Jung, Synthesis of Tin Oxide Nanoparticle Film by Cathodic Electrodeposition, *Journal of Nanoscience and Nanotechnology* **12** (2012) 1616-1619. https://doi.org/10.1166/jnn.2012.4646

[87] M. Lai, J. A. Martinez, M. Grätzelb, D. J. Riley, Preparation of tin dioxidenanotubesvia electrosynthesis in a template, *Journal of Materials Chemistry* **16** (2006) 2843-2845. https://doi.org/10.1039/B606433G

[88] R. L. Spray, K.-Sh. Choi, Electrochemical synthesis of SnO_2 films containing three-dimensionally organized uniform mesopores *via* interfacial surfactant templating, *Chemical Communications* (2007) 3655-3657. https://doi.org/10.1039/B704428C

[89] T. Ishizaki, N. Saito, O. Takai, Surfactant-Assisted Fabrication of Tin Oxide Nanowires Through One-Step Electrochemically Induced Chemical Deposition, *Journal of The Electrochemical Society* **156** (2009) D413. https://doi.org/10.1149/1.3190161

[90] R. Alaufey, L. Zhao, C. Lents, B. Markunas, A. D. Walter, Q. Wu, J. A. Keith, M. Tang, Electrochemical Corrosion and Catalysis Dynamics of Tin Oxide during Water Oxidation. *ACS Catalysis* **15(21)** (2025) 18601-18611. https://doi.org/10.1021/acscatal.5c04461

[91] J. Li, L. Chang, B. Chen, H. Huang, Z. Guo, Study on the Performance and Corrosion Failure Process of Porous Titanium-Based Coated Electrodes, *Lubricants* **10** (2022) 282. https://doi.org/10.3390/lubricants10110282

[92] F. Montilla, E. Morallón, A. De Battisti, J. L. Vázquez, Preparation and characterization of antimony-doped tin dioxide electrodes. Part 1. Electrochemical characterization, *The Journal of Physical Chemistry B* **108** (16) (2004) 5036-5043. https://doi.org/10.1021/jp048674+

[93] F. Montilla, E. Morallón, A. De Battisti, A. Benedetti, H. Yamashita, J. L. Vázquez, Preparation and characterization of antimony-doped tin dioxide electrodes. Part 2. XRD and EXAFS characterization, *The Journal of Physical Chemistry B* **108(16)** (2004) 5044-5050. https://doi.org/10.1021/jp0374814

[94] A. Xu, X. Dai, K. Wei, W. Han, J. Li, X. Sun, J. Shen, L. Wang, Preparation and characterization of a TiO_2-NT/SnO_2-Sb tubular porous electrode with long service lifetime

for wastewater treatment process, *RSC Advances* **7** (60) (2017) 37806-37814. https://doi.org/10.1039/C7RA05127A

[95] X. Chen, G. Chen, Investigation of Ti／IrO_2-Sb_2O_5-SnO_2 Electrodes for O_2 Evolution: Calcination Temperature and Precursor Composition Effects, *Journal of The Electrochemical Society* **152** (2005) J59-J64. https://doi.org/10.1149/1.1922890

[96] Y. Li, F. Wang, G. Zhou, Y. Ni, Aniline degradation by electrocatalytic oxidation, *Chemosphere* **53** (2003) 1229-1234. https://doi.org/10.1016/S0045-6535(03)00590-3

[97] R. D. Coteiro, F. S. Teruel, J. Ribeiro, A. R. de Andrade, Effect of solvent on the preparation and characterization of DSA-type anodes containing RuO_2-TiO_2-SnO_2, *Journal of the Brazilian Chemical Society* **17** (2006) 771-779. https://doi.org/10.1590/S0103-50532006000400020

[98] C. A. Martínez-Huitle, E. Brillas, Electrochemical alternatives for drinking water disinfection, *Angewandte Chemie International Edition* **47** (11) (2008) 1998-2005. https://doi.org/10.1002/anie.200703621

[99] A. Anglada, A. Urtiaga, I. Ortiz, Contributions of electrochemical oxidation to waste-water treatment: fundamentals and review of applications. *Journal of Chemical Technology & Biotechnology* **84** (12) (2009) 1747-1755. https://doi.org/10.1002/jctb.2214

[100] A. Kraft, Doped diamond: a compact review on a new, versatile electrode material, *International Journal of Electrochemical Science* **2** (5) (2007) 355-385. https://doi.org/10.1016/S1452-3981(23)17080-5

[101] D. Shao, W. Yan, X. Li, H. Yang, H. Xu, A highly stable Ti/TiH_x/Sb-SnO_2 anode: preparation, characterization and application, *Industrial & Engineering Chemistry Research* **53** (10) (2014) 3898-3907. https://doi.org/10.1021/ie403768f

[102] X. Chen, G. Chen, F. Gao, P. L. Yue, High-Performance Ti/BDD Electrodes for Pollutant Oxidation, *Environmental Science & Technology* **37** (2003) 5021-5026. https://doi.org/10.1021/es026443f

[103] C. A. M. Huitle, E. Brillas, Decontamination of wastewaters containing synthetic organic dyes by electrochemical methods: A general review, *Applied Catalysis B: Environmental* **87** (2009) 105-145. https://doi.org/10.1016/j.apcatb.2008.09.017

[104] A. M. Polcaro, S. Palmas, F. Renoldi, M. Mascia, On the performance of Ti/SnO_2 and Ti/PbO_2 anodes in electrochemical degradation of 2-chlorophenolfor wastewater treatment, *Journal of Applied Electrochemistry* **29** (1999) 147-151. https://doi.org/10.1023/A:1003411906212

[105] F. Bonfatti, S. Ferro, F. Lavezzo, M. Malacarne, G. Lodi, A. De Battisti, Electrochemical Incineration of Glucose as a Model Organic Substrate. I. Role of the Electrode Material, *Journal of The Electrochemical Society* **146** (1999) 2175-2179. https://doi.org/10.1149/1.1391909

[106] R. Kötz, S. Stucki, B. Carcer, Electrochemical waste water treatment using high overvoltage anodes. Part I: Physical and electrochemical properties of SnO_2 anodes, *Journal of Applied Electrochemistry* **21** (1991) 14-20. https://doi.org/10.1007/BF01103823

[107] C. Comninellis, Electrochemical treatment of waste water containing phenol, *Electrochemical Engineering and the Environment* **92** (1992) 189-201. https://doi.org/20.500.14299/225283

[108] C. S. Fugivara, P. T. A. Sumodjo, A. A. Cardoso, A. V. Benedetti, Electrochemical decomposition of cyanides on tin dioxide electrodes in alkaline media, *Analyst* **121** (1996) 541-545. https://doi.org/10.1039/AN9962100541

[109] H. Bouya, M. Errami, R. Salghi, Lh. Bazzi, A. Zarrouk, S.S. Al-Deyab, B. Hammouti, L. Bazzi, A. Chakir, Electrochemical Degradation of Cypermethrin Pesticide on a SnO_2 Anode,

International Journal of Electrochemical Science **7** (2012) 3453-3465. https://doi.org/10.1016/S1452-3981(23)13968-X

[110] S. Man, Z. Yin, S. Zhou, E. Pameté, L. Xu, H. Bao, W. Yang, Z. Mo, V. Presser, X. Li, Novel Sb−SnO_2 Electrode with Ti^{3+} Self-Doped Urchin-Like Rutile TiO_2 Nanoclusters as the Interlayer for the Effective Degradation of Dye Pollutants, *ChemSusChem* **16** (2023) e202201901. https://doi.org/10.1002/cssc.202201901

[111] H. J. Nsaif, N. S. Majeed, R. H. Salman, Preparation of nano SnO_2-Sb_2O_3 composite electrode by cathodic deposition for the elimination of phenol by Sonoelectrochemical oxidation, *Green Sciences* **26** (2024) 21-28. https://doi.org/10.2478/pjct-2024-0026

[112] A. Baciu, C. Orha, R. Nicolae, M. Nicolaescu, S. Ilies, F. Manea, Advanced Electrochemical Degradation of Organic Pollutants from Water Using Sb-Doped SnO_2/Ti Anode and Assisted by Granular Activated Carbon, *Coatings* **13** (2023) 1127. https://doi.org/10.3390/coatings13061127

[113] S. Chen, L. Zhou, T. Yang, Q. He, P. Zhou, P. He, F. Dong, H. Zhang, B. Jia, Thermal decomposition based fabrication of dimensionally stable Ti/SnO_2-RuO_2 anode for highly efficient electrocatalytic degradation of alizarin cyanin green, *Chemosphere* **261** (2020) 128201. https://doi.org/10.1016/j.chemosphere.2020.128201

[114] M. Panizza, C. A. Martinez-Huitle, Role of electrode materials for the anodic oxidation of a real landfill leachate - Comparison between Ti-Ru-Sn ternary oxide, PbO_2 and boron-doped diamond anode, *Chemosphere* **90** (2013) 1455-1460. https://doi.org/10.1016/j.chemosphere.2012.09.006

[115] L.-C. Chiang, J.-E. Chang, T.-C. Wen, Indirect oxidation effect in electrochemical oxidation treatment of landfill leachate, *Water Research* **29** (1995) 671-678. https://doi.org/10.1016/0043-1354(94)00146-X

[116] J. P. Ruparelia, B. D. Soni, Application of Ti/RuO_2-SnO_2-Sb_2O_5 anode for degradation of reactive black-5 dye, *International Journal of Chemical and Molecular Engineering* **6** (11) (2012) 715-721. https://doi.org/10.5281/zenodo.1070603

[117] M. I. León, Z. G. Aguilar, J. L. Nava, Electrochemical combustion of indigo at ternary oxide coated titanium anodes, *Journal of Electrochemical Science and Engineering* **4** (2014) 247-258. https://doi.org/10.5599/jese.2014.0061

[118] A. M. Z. Ramalho, C. A. Martínez-Huitle, D. R. da Silva, Application of electrochemical technology for removing petroleum hydrocarbons from produced water using a DSA-type anode at different flow rates, *Fuel* **89** (2010) 531-534. https://doi.org/10.1016/j.fuel.2009.07.016

[119] L. L. Houk, S. K. Johnson, J. Feng, R. S. Houk, D. C. Johnson, Electrochemical incineration of benzoquinone in aqueous media using a quaternary metal oxide electrode in the absence of a soluble supporting electrolyte, *Journal of Applied Electrochemistry* **28** (1998) 1167-1177. https://doi.org/10.1023/A:1003439727317

[120] F. Yu, S. Hong, B. Guo, X. Ren, X. Zhou, TiO_2 Nanotubes Array Based Ti/TiO_2NTs/SnO_2-Sb-Bi/NATO Electrode for Electrosynthesis of Ozone Water and Application in Wastewater Treatment, *Materials Science in Semiconductor Processing* **186** (2025) 109098. https://doi.org/10.1016/j.mssp.2024.109098

[121] Y. Cen, Y. Zhou, M. Zhu, K. Zheng, S. Zhou, Preparation of the Ti/TiO_2-RNTs/SnO_2-Sb-Ni-La Electrode and Its Electrochemical Degradation of Oily Wastewater, *Langmuir* **41** (2025) 8766-8780. https://doi.org/10.1021/acs.langmuir.4c05356

[122] J. Grimm, D. Bessarabov, W. Maier, S. Storck, R.D. Sanderson, Sol-gel film-preparation of novel electrodes for the electrocatalytic oxidation of organic pollutants in water, *Desalination* **115** (1998) 295-302. https://doi.org/10.1016/S0011-9164(98)00048-4

[123] Y. Zhang, S. Ge, M. Shao, W. Ke, L. Tao, X. Zhou, Optimization of a Mn-Doped Ti/SnO_2-Sb Anode for Electrochemical Treatment of Dye Wastewater, *Journal of Electronic Materials* **51** (2022) 1041-1047. https://doi.org/10.1007/S11664-021-09342-4

[124] X. Chen, G. Chen, P. Lock Yue, Anodic oxidation of dyes at novel Ti/B-diamond electrodes, *Chemical Engineering Science* **58** (2003) 995-1001. https://doi.org/10.1016/S0009-2509(02)00640-1

[125] J. Hastie, D. Bejan, M. Teutli-León, N.J. Bunce, Electrochemical methods for degradation of Orange II (sodium 4-(2-hydroxy-1-naphthylazo) benzenesulfonate), *Industrial and Engineering Chemistry Research* **45** (2006) 4898-4904. https://doi.org/10.1021/ie060310b

[126] M. Panizza, G. Cerisola , Influence of anode material on the electrochemical oxidation of 2-naphthol: Part 2. Bulk electrolysis experiments, *Electrochimica Acta* **49** (2004) 3221-3226. https://doi.org/10.1016/j.electacta.2004.02.036

[127] M Panizza, G. Cerisola, Influence of anode material on the electrochemical oxidation of 2-naphthol: Part 1. Cyclic voltammetry and potential step experiments, *Electrochimica Acta* **48** (2003) 3491-3497. https://doi.org/10.1016/S0013-4686(03)00468-7

[128] M. Panizza, G. Cerisola, Electrocatalytic materials for the electrochemical oxidation of synthetic dyes, *Applied Catalysis B: Environmental* **75** (2007) 95-101. https://doi.org/10.1016/j.apcatb.2007.04.001

[129] T. Le Luu, P. Thi Kim Ngan, Fabrication of high performance Ti/SnO_2-Nb_2O_5 electrodes for electrochemical textile wastewater treatment, *Science of The Total Environment* **860** (2023) 160366. https://doi.org/10.1016/j.scitotenv.2022.160366

[130] C. Zhao, Z. Wu, J. Lai, L. Liu, H. Li, H. Wang, Efficient electrochemical oxidation of refractory organics in actual petrochemical reverse osmosis concentrates by Ti/SnO_2-Sb mesh anode, *Process Safety and Environmental Protection* **182** (2024) 1060-1071. https://doi.org/10.1016/j.psep.2023.12.067

[131] H. Al-Tameemi, K. Sukkar, A. Abbar, Electrochemical preparation and characterization of a new configuration SnO_2 anode and its application for treating petroleum refinery wastewater, *Results in Engineering* **22** (2024) 102147. https://doi.org/10.1016/j.rineng.2024.102147

[132] J. Ma, T. Wang, Y. Zhao, F. Chang, Fabrication of Ti/SnO_2-Sb electrodes containing RuO_2 interlayer for efficient electrocatalytic oxidation of caprolactam wastewater, *International Journal of Electrochemical Science* **19** (2024) 100460. https://doi.org/10.1016/j.ijoes.2024.100460

[133] T. P. Wai, Y. Yin, X. Zhang, Z. Li, Preparation and Characterization of Rare Earth-Doped Ti/SnO_2-Sb-Mn Electrodes for the Electrocatalytic Performance, *Journal of Nanomaterials* (2020) 8958043. https://doi.org/10.1155/2020/8958043

[134] F. L. Zhu, Y. S. Meng, X. Y. Huang, Electro-catalytic degradation properties of Ti/SnO_2-Sb electrodes doped with different rare earths, *Rare Metals* **35** (2016) 412-418. https://doi.org/10.1007/s12598-014-0397-x

[135] L. Li, Z. Huang, X. Fan, Z. Zhang, R. Dou, S. Wen, Y. Chen, Y. Hu, Preparation and characterization of a Pd modified Ti/SnO_2-Sb anode and its electrochemical degradation of Ni-ETA, *Electrochimica Acta* **231** (2017) 354-362. https://doi.org/10.1016/j.electacta.2017.02.072

[136] S. Yang, Y. Choo, S. Kim, S. Lim, J. Lee, H. Park, Boosting the electrocatalytic activities of SnO_2 electrodes for remediation of aqueous pollutants by doping with various metals, *Applied Catalysis B: Environmental* **111-112** (2012) 317-325. https://doi.org/10.1016/j.apcatb.2011.10.014

[137] R. Berenguer, J.M. Sieben, C. Quijada, E. Morallón, Electrocatalytic degradation of phenol on Pt-and Ru-doped Ti/SnO_2-Sb anodes in an alkaline medium, *Applied Catalysis B: Environmental* **199** (2016) 394-404. https://doi.org/10.1016/j.apcatb.2016.06.038

[138] J. Liang, C. Geng, D. Li, L. Cui, X. Wang, Preparation and degradation phenol characterization of Ti/SnO_2-Sb-Mo electrode doped with different contents of molybdenum, *Journal of Materials Science & Technology* **31** (2015) 473-478. https://doi.org/10.1016/j.jmst.2014.11.025

[139] Y. Wang, H. Duan, Z. Pei, L. Xu, Hydrothermal synthesis of 3D hierarchically flower-like structure Ti/SnO_2-Sb electrode with long service life and high electrocatalytic performance, *Journal of Electroanalytical Chemistry* **855** (2019) 113635. .https://doi.org/10.1016/j.jelechem.2019.113635

[140] P. Li, G. Zhao, X. Cui, Y. Zhang, Y. Tang, Constructing Stake Structured TiO_2-NTs/Sb-Doped SnO_2 Electrode Simultaneously with High Electrocatalytic and Photocatalytic Performance for Complete Mineralization of Refractory Aromatic Acid, *The Journal of Physical Chemistry C* **113** (2009) 2375-2383. https://doi.org/10.1021/jp8078106

[141] B. Tang, M. Liu, G. Zhao, *Preparation of TiO_2, Nanotubes-Based Electrophotocatalysts and Their Applications in Organic Pollutants Oxidation,* in: *Nanostructured Photocatalysts, Advanced Functional Materials,* H. Yamashita, X. Li, Eds., Springer Cham, 2016, 125-136. https://doi.org/10.1007/978-3-319-26079-2_6

[142] S. Chai, G. Zhao, P. Li, Y. Lei, Y.-N. Zhang, D. Li, Novel Sieve-Like SnO_2/TiO_2 Nanotubes with Integrated Photoelectrocatalysis: Fabrication and Application for Efficient Toxicity Elimination of Nitrophenol, *The Journal of Physical Chemistry C* **115** (2011) 18261-18269. https://doi.org/10.1021/jp205228h

[143] N. A. Rosli, S. F. M. Shairuddin, E. Mahmoudi, W. L. Ang, Advancements in SnO_2-modified electrodes for electrochemical oxidation of persistent organic pollutants: Mechanisms, Challenges, and opportunities, *Chemical Engineering Journal Advances* **24** (2025) 100876. https://doi.org/10.1016/j.ceja.2025.100876

[144] D. Knozowski, M. Gmurek, Non-active anodes based on boron-doped diamond, PbO_2 and SnO_2-Sb for anodic oxidation of water contaminants: Synthesis, properties, and recent advances, *Desalination and Water Treatment* **320** (2024) 100655. https://doi.org/10.1016/j.dwt.2024.100655

[145] T. Guo, X. Chen, L. Yin, Recent advancements in modified SnO_2-Sb electrodes for electrochemical treatment of wastewater, *Journal of Materials Chemistry A* **12** (2024) 4397-4420. https://doi.org/10.1039/D3TA07238J