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Dual-Function Nanostructured Anodes for Simultaneous Electrochemical Degradation of Organic Pollutants and In-Situ Corrosion Protection of Metallic Substrates

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ABSTRACT

Electrochemical advanced oxidation processes (EAOPs) have emerged as promising technologies for the degradation of persistent organic pollutants (POPs) through the in-situ generation of reactive oxygen species, particularly hydroxyl radicals (•OH). However, the practical application of EAOPs faces two critical challenges: the competitive chloride oxidation reaction (COR) caused by chloride ions in real wastewater, which leads to low Faradaic efficiency and severe corrosion of anode active sites, and the limited service life of electrodes due to dissolution of catalytic layers under harsh operating conditions. This comprehensive review systematically examines nanostructured anodes designed for dual-function applications simultaneously achieving efficient electrochemical degradation of organic pollutants while providing in-situ corrosion protection of metallic substrates. Nanostructuring approaches, including TiO_2 nanotube arrays and hydrophobic surface modification, have demonstrated remarkable performance enhancement: TiO_2-NTs/SnO_2-Sb-PTFE composite electrodes achieve high oxygen evolution potential (2.4 V vs Ag/AgCl), significantly enhanced TOC removal efficiency for phenolic pollutants, and substantial reduction in Sn ion leaching compared to conventional electrodes . Surface hydrophobicity promotes effective release of free hydroxyl radicals from the anode surface into solution, facilitating pollutant mineralization while the hydrophobic PTFE layer acts as a barrier inhibiting anodic dissolution. Anti-corrosion design principles for seawater electrolysis including selective oxygen evolution reaction active sites, anion exclusion layers, and electronic structure redistribution offer valuable strategies for enhancing anode stability in chloride-rich environments. Recent advances in iridium-coated titanium anodes demonstrate service lives of 2-5 years with iridium loss below 0.1 mg/cm^2/year, while PANI-modified iron anodes achieve corrosion inhibition efficiency of approximately 35% after repeated electrocoagulation treatment cycles. This review concludes that dual-function anodes represent a transformative approach for sustainable wastewater treatment, combining catalytic activity with corrosion resistance.

Introduction

The increasing global demand for freshwater, coupled with the discharge of persistent organic pollutants (POPs) into water bodies, has created an urgent need for effective and sustainable wastewater treatment technologies.

Traditional biological treatment methods often prove insufficient for recalcitrant compounds such as phenols, pharmaceuticals, and endocrine-disrupting chemicals, which exhibit resistance to biodegradation and pose significant risks to human health and ecosystems.

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Electrochemical advanced oxidation processes (EAOPs) have emerged as a promising alternative, offering versatility, environmental compatibility, and the capability to mineralize organic pollutants through the in-situ generation of highly reactive oxygen species, particularly hydroxyl radicals (•OH).

The fundamental mechanism of electrochemical oxidation involves the generation of reactive species at the anode surface. Under an applied potential, water molecules are oxidized to form physiosorbed hydroxyl radicals (•OH) on the anode surface. These radicals exhibit high oxidation power (E°=2.59 V vs SHE) and can non-selectively attack organic molecules, ultimately leading to their complete mineralization to CO_2 and H_2O. Alternatively, in the presence of chloride ions, active chlorine species (Cl_2, HClO, ClO^-) are generated, which can also oxidize organic pollutants through indirect oxidation mechanisms. The efficiency of these processes depends critically on the anode material, its surface properties, and the operating conditions.

Despite their promise, the practical application of EAOPs faces two interconnected challenges. First, the chloride oxidation reaction (COR) in chloride-rich wastewaters competes with oxygen evolution and organic oxidation, reducing Faradaic efficiency and generating corrosive species that attack the anode surface. Second, the dissolution of the catalytic layer particularly Sn ions from SnO_2-based anodes leads to gradual degradation of electrode performance and secondary pollution. These limitations have motivated extensive research into nanostructured anode materials that combine high catalytic activity with enhanced corrosion resistance.

The concept of "dual-function" anodes integrates these two requirements into a unified design: electrodes that efficiently degrade organic pollutants while simultaneously protecting the underlying metallic substrate from corrosion. This approach leverages Nano structuring strategies including TiO_2 nanotube arrays, hydrophobic surface modification, and composite structures to enhance both electrocatalytic activity and electrode stability. This comprehensive review systematically examines the synthesis, characterization, and performance of dual-function nanostructured anodes, with particular emphasis on the mechanisms governing pollutant degradation and corrosion protection.

Literature Review

Electrochemical Oxidation Mechanisms

Electrochemical oxidation proceeds through two primary pathways: direct oxidation at the anode surface and indirect oxidation mediated by electrogenerated oxidants. Direct oxidation involves the transfer of electrons from organic pollutants to the anode surface, occurring at high overpotentials and typically leading to partial oxidation or complete mineralization depending on the anode material. Indirect oxidation involves the generation of reactive species primarily hydroxyl radicals (•OH) which diffuse into the solution and react with organic pollutants.

The formation of hydroxyl radicals at the anode surface is governed by the oxygen evolution potential (OEP) of the electrode material. Anodes with high OEP favor the formation of physiosorbed •OH radicals, which are available for organic oxidation, while anodes with low OEP promote the formation of chemisorbed oxygen species that favor oxygen evolution. TiO_2-NTs/SnO_2-Sb-PTFE electrodes exhibit high OEP (2.4 V vs Ag/AgCl), enabling efficient •OH generation and TOC removal. In chloride-containing electrolytes, chloride ions can be oxidized to active chlorine species (Cl_2, HClO, ClO^-), which provide an additional indirect oxidation pathway. The formation of active chlorine is pH-dependent: Cl_2 predominates at pH ≤ 3, HClO at 3 < pH < 8, and ClO^- at pH ≥ 8.

Nanostructured Anode Materials:

The development of nanostructured anodes has focused on enhancing the active surface area, improving electron transfer kinetics, and promoting the generation of reactive species. Titanium dioxide nanotube (TiO_2-NT) arrays, formed by anodic oxidation of titanium substrates, provide a high-surface-area, vertically oriented architecture that serves as an excellent support for catalytic coatings. The incorporation of SnO_2-Sb catalysts into TiO_2-NT arrays has yielded electrodes with significantly enhanced electrocatalytic performance.

Hydrophobic surface modification has emerged as a key strategy for enhancing oxidation efficiency. PTFE-modified TiO_2-NTs/SnO_2-Sb electrodes exhibit highly hydrophobic surfaces that promote the effective release of free hydroxyl radicals from the anode surface into the solution. This facilitates pollutant mineralization while minimizing the competitive oxygen evolution reaction. The PTFE layer also acts as a barrier inhibiting anodic dissolution, reducing Sn ion leaching compared to conventional electrodes.

Corrosion Mechanisms in Electrochemical Systems:

The corrosion of anodes in electrochemical oxidation systems arises from several mechanisms. In chloride-containing electrolytes, chloride ions can be adsorbed onto the metal active sites and coordinate with the framework metals to form soluble chlorides. These soluble chlorides subsequently form metal hydroxides in alkaline

environments, leading to progressive dissolution of the catalytic layer. The corrosion mechanism involves: (1) adsorption of Cl^- onto the metal active site at high anodic potentials; (2) coordination of Cl^- with framework metals to form soluble chlorides; and (3) formation of metal hydroxides from the soluble chlorides.

The dissolution of Sn ions from SnO_2-based anodes is a particular concern, as it leads to gradual loss of catalytic activity and secondary pollution. The leaching of Sn ions is influenced by solution pH, with acidic conditions promoting dissolution and basic conditions inhibiting it. PTFE modification of TiO_2-NTs/SnO_2-Sb electrodes effectively inhibit Sn ion leaching by creating a barrier between the electrolyte and the SnO_2 layer.

Anti-Corrosion Design Strategies

Recent advances in anti-corrosion design for anodes in seawater electrolysis have identified four key strategies relevant to dual-function electrodes. Selective oxygen evolution reaction (OER) active sites can be designed to favor OER over chloride oxidation, reducing the generation of corrosive species. Anti-corrosion strategies include introducing anion exclusion layers that repel chloride ions from the electrode surface and modifying the electronic structure distribution through elemental doping. Asymmetric electrolytic cell designs can also mitigate corrosion by controlling the distribution of reactive species.

Electrode coatings with noble metals such as tantalum, titanium, niobium, zirconium, hafnium, vanadium, molybdate, and tungsten improve electrode stability through enhanced corrosion resistance. Iridium-coated titanium anodes (IrO_2/Ti) exhibit service lives of 2-5 years with iridium loss below 0.1 mg/cm²/year, demonstrating the effectiveness of noble metal coatings. The combination of corrosion-resistant substrates with nanostructured catalytic layers represents the frontier of dual-function anode design.

Methodology

This comprehensive review was developed through systematic analysis of peer-reviewed literature indexed in major scientific databases including Scopus, Web of Science, ScienceDirect, and Google Scholar. The search strategy employed combinations of keywords including "electrochemical oxidation," "nanostructured anodes," "corrosion protection," "organic pollutant degradation," "titanium dioxide nanotubes," "SnO_2 electrodes," "hydrophobic modification," and related terms. Particular emphasis was placed on studies published between 2015 and 2026, while seminal earlier works were included were mechanistically or technologically significant.

The literature screening process involved identification of peer-reviewed research articles, review papers, conference proceedings, and relevant patents. Studies were selected based on relevance to the review scope, methodological rigor, completeness of reported experimental conditions, and applicability to dual-function anode technology. Representative studies for comparative analysis were chosen based on clear presentation of synthesis methodology, characterization results, and performance metrics. Publications lacking sufficient methodological detail or quantitative performance data were excluded.

Quantitative data synthesis focused on anode performance metrics including oxygen evolution potential, TOC removal efficiency, specific energy consumption, Sn ion leaching concentration, and service life. Synthesis methods were evaluated based on reported electrode characteristics including surface morphology, hydrophobicity, and electrochemical properties. Corrosion protection performance was assessed through analysis of metal ion leaching, electrode lifetime, and corrosion inhibition efficiency.

Results

Table 1. Performance of TiO_2-NTs/SnO_2-Sb-PTFE Electrodes for Phenol Degradation

Electrode Type	PTFE Loading (mL/L)	OEP (V vs Ag/AgCl)	TOC Removal (%)	SUVA254 Degradation	Sn Leaching ($\times10^{-5}$ M)
Conventional Ti/SnO_2-Sb	N/A	~1.8	64	Moderate	11.0
TiO_2-NTs/SnO_2-Sb	0	~2.0	73	Moderate	7.8
TiO_2-NTs/SnO_2-Sb-PTFE	1.5	~2.2	78	Enhanced	7.5
TiO_2-NTs/SnO_2-Sb-PTFE	4.5	2.4	82	Significantly enhanced	7.1
TiO_2-NTs/SnO_2-Sb-PTFE	13.5	~2.2	75	Enhanced	3.6

Data compiled from reference.

Analysis of Table 1: The comparative analysis demonstrates that PTFE modification substantially enhances the performance of TiO_2-NTs/SnO_2-Sb electrodes for electrochemical oxidation of phenol. The oxygen evolution potential (OEP) increases from ~1.8 V for conventional Ti/SnO_2-Sb to 2.4 V for TiO_2-NTs/SnO_2-Sb-PTFE (4.5), representing a significant improvement in resistance to the parasitic oxygen evolution reaction. This higher OEP enables more efficient generation of free hydroxyl radicals (•OH) at the anode surface, as evidenced by the TOC removal efficiency increasing from 64% to 82% under identical conditions.

The hydrophobic surface created by PTFE modification plays a dual role in enhancing performance. First, it promotes the effective release of free hydroxyl radicals from the anode surface into the solution, facilitating pollutant mineralization. Second, the PTFE layer acts as a barrier between the electrolyte and the SnO_2 layer, significantly reducing Sn ion leaching. At pH 3, Sn dissolved concentration was 1.1×10^{-4} M using the conventional Ti/SnO_2-Sb anode, while TiO_2-NTs/SnO_2-Sb-PTFE electrodes released only 7.1×10^{-5} M to 8.0×10^{-5} M. At pH 11, Sn leaching was further reduced to 3.6×10^{-6} M for TiO_2-NTs/SnO_2-Sb-PTFE (13.5).

The reduced Sn leaching has important implications for both electrode stability and environmental safety. The loss of Sn ions from the catalytic layer leads to progressive degradation of electrode performance over time. By inhibiting this dissolution, PTFE modification extends the service life of the electrode while minimizing secondary pollution. The optimal PTFE loading of 4.5 mL/L provides the best balance of high OEP, efficient pollutant degradation, and reduced Sn leaching.

Table 2. Anti-Corrosion Strategies for Anodes in Seawater Electrolysis

Strategy	Mechanism	Key Application	Reported Benefits	Challenges
Selective OER Active Sites	Favor OER over COR; reduce Cl^- adsorption	Transition metal oxides/hydroxides	Enhanced Faradaic efficiency	Complex catalyst design
Anion Exclusion Layer	Repel Cl^- from electrode surface; create anion buffer layer	Surface-modified anodes	Reduced chloride oxidation; enhanced stability	Layer stability; fabrication complexity
Electronic Structure Redistribution	Elemental doping; heterogeneous structure; defect engineering	Doped transition metal-based catalysts	Improved conductivity; enhanced OER kinetics	Optimal doping level; long-term stability
Asymmetric Electrolytic Cell Design	Control potential/current distribution; separate anodic/cathodic environments	Electrolyzer configuration	Reduced COR; enhanced overall efficiency	System complexity; scale-up challenges
Noble Metal Coatings (Ir, Ru, Pt)	Catalytic activity + corrosion resistance	IrO_2/Ti, RuO_2/Ti anodes	Service life 2-5 years; Ir loss <0.1 mg/cm²/year	High cost; noble metal scarcity
Conductive Polymer Coatings (PANI, PPy)	Physical barrier + electronic protection	Modified Fe anodes for EC	Corrosion inhibition efficiency ~35%; heavy metal removal >98%	Polymer stability; adhesion

Data compiled from references.

Analysis of Table 2: The comprehensive anti-corrosion strategies identified for anodes in seawater electrolysis provide a valuable framework for dual-function anode design. Selective OER active sites represent the most fundamental approach, were catalyst design favors water oxidation over chloride oxidation, thereby reducing corrosive chloride species generation. The creation of anion exclusion layers that repel chloride ions from the electrode surface has emerged as a promising complementary strategy, though layer stability under long-term operation remains challenging.

Electronic structure redistribution through elemental doping, heterogeneous structure construction, and defect engineering has been widely applied to transition metal-based materials to enhance both OER activity and corrosion resistance. These modifications can shift the d-band center, modify adsorption energetics, and improve charge transfer kinetics. Asymmetric electrolytic cell designs offer system-level corrosion mitigation by controlling potential distribution and separating anodic and cathodic environments.

Noble metal coatings demonstrate the most robust corrosion protection, with iridium-coated titanium anodes exhibiting service lives of 2-5 years and iridium loss below 0.1 mg/cm²/year. However, the high cost and limited availability of noble metals motivate continued development of alternative materials. Conductive polymer coatings, particularly polyaniline (PANI), offer a cost-effective approach, achieving corrosion inhibition efficiency of approximately 35% while maintaining heavy metal removal efficiency above 98%. The dual-function capability combining corrosion protection with electrocoagulation activity makes PANI-modified anodes particularly attractive for wastewater treatment applications.

Table 3. Electrode Stability and Service Life Comparison

Anode Type	Degradation Mechanism	Service Life	Key Stability Factors	Operating Conditions
Conventional Ti/SnO_2-Sb	Sn ion dissolution; catalytic layer detachment	Limited (hours to days)	Calcination temperature; current density	Acidic pH accelerates dissolution
TiO_2-NTs/SnO_2-Sb-PTFE	Sn ion dissolution reduced by PTFE barrier; structural stability enhanced	Extended (days to weeks)	PTFE loading; TiO_2 nanotube support	High OEP reduces H^+ generation; inhibits Sn leaching
IrO_2/Ti (Iridium-coated)	Iridium loss; coating detachment	2-5 years	Coating composition; substrate preparation	pH 2-12; up to 60°C; low Ir loss
RuO_2-IrO_2/Ti	Noble metal loss; substrate corrosion	Enhanced compared to single oxide	Binary oxide structure improves lifetime	Mixed oxide composition enhances stability
PANI-Modified Fe Anode	Polymer degradation; substrate corrosion	Extended (10+ treatment cycles)	PANI-MMT composite; hydrophobic barrier	20 mA/cm²; pH 7; corrosion inhibition ~35%

Data compiled from references.

Analysis of Table 3: The stability and service life of electrochemical anodes vary dramatically across material systems, reflecting fundamental differences in degradation mechanisms. Conventional Ti/SnO_2-Sb anodes suffer from Sn ion dissolution, particularly under acidic conditions where the final solution pH becomes low due to H^+ generation during oxygen evolution. The high OEP of TiO_2-NTs/SnO_2-Sb-PTFE electrodes inhibits oxygen evolution, reducing H^+ generation and thus inhibiting Sn leaching. The presence of the PTFE layer provides an additional barrier between the electrolyte and SnO_2, further reducing dissolution.

Iridium-coated titanium anodes (IrO_2/Ti) represent the current commercial standard for demanding electrochemical oxidation applications, with service lives of 2-5 years depending on pollutant load and operating conditions. The iridium loss rate is maintained below 0.1 mg/cm²/year, demonstrating the effectiveness of noble metal coatings in providing long-term stability. Binary oxide systems (RuO_2-IrO_2) offer enhanced stability compared to single oxides, with the intermediate compound structure providing higher lifetime than binary oxides.

Conductive polymer coatings, particularly PANI-modified iron anodes, demonstrate extended service life through corrosion inhibition. The PANI-MMT coated anode achieves corrosion inhibition efficiency of approximately 35% even after 10 repeated electrocoagulation treatment cycles. The negative adsorption energy of PANI-MMT (-183.59 kJ/mol) indicates strong interaction with the substrate surface, contributing to the protective layer stability. The hydrophobic nature of the coating also provides gas-liquid barrier properties, further inhibiting corrosion.

Table 4. Dual-Function Performance Metrics: Pollutant Degradation and Corrosion Protection

Anode System	Pollutant	Degradation Efficiency (%)	Corrosion Protection Performance	Operation Conditions	Dual-Function Mechanism
TiO_2-NTs/SnO_2-Sb-PTFE	Phenol	82% TOC removal	Sn leaching: 7.1×10^{-5} M (85%	2.4 V OEP; pH 7; Na_2SO_4	Hydrophobic PTFE: •OH release

			reduction vs conventional)		+ Sn leaching barrier
IrO_2/Ti	Various	>90% BTX removal	Service life: 2-5 years; Ir loss <0.1 mg/cm²/year	Cell voltage 2.5-4.0 V; pH 2-12	Noble metal: Catalytic activity + corrosion resistance
PANI-MMT/Fe	Zn, Ni removal	Zn: 98.4%; Ni: 80.7%	Corrosion inhibition: ~35% after 10 cycles	20 mA/cm²; pH 7; 100 min	PANI coating: Conductive + protective barrier
SnO_2-Sb-CNT Duplex	BPA	Enhanced adsorption + degradation	Sn leaching reduced by CNT composite	Duplex structure; adsorption + oxidation	Adsorption enhancement + structural stability

Data compiled from references.

Analysis of Table 4: The dual-function performance of nanostructured anodes demonstrates the feasibility of combining efficient pollutant degradation with effective corrosion protection. The TiO_2-NTs/SnO_2-Sb-PTFE system achieves 82% TOC removal of phenol while reducing Sn leaching by approximately 85% compared to conventional electrodes. This dual-function capability is attributed to the hydrophobic PTFE layer, which simultaneously promotes effective release of free hydroxyl radicals into the solution (enhancing pollutant mineralization) and acts as a barrier inhibiting anodic dissolution (enhancing corrosion protection).

Iridium-coated titanium anodes demonstrate robust dual-function performance across diverse applications, with >90% removal efficiency for BTX compounds and service lives of 2-5 years. The noble metal coating provides both catalytic activity for pollutant degradation and corrosion resistance in aggressive environments (pH 2-12, up to 60°C). The dual-function mechanism operates through the IrO_2 surface reducing oxygen evolution overpotential while the stable oxide coating protects the titanium substrate.

PANI-MMT modified iron anodes achieve heavy metal removal efficiencies of 98.4% for Zn and 80.7% for Ni while providing corrosion inhibition of approximately 35% after repeated treatment cycles. The conductive polymer coating functions as both an electrochemically active surface for pollutant removal and a protective barrier against substrate corrosion. The negative adsorption energy of PANI-MMT (-183.59 kJ/mol) indicates strong surface interaction, contributing to the sustained protective effect.

The SnO_2-Sb-CNT duplex electrode demonstrates a different dual-function approach, combining adsorption enhancement with electrochemical oxidation for BPA removal. The CNT composite increases surface area and adsorption capacity, bringing pollutants into close proximity with the catalytic surface while simultaneously improving structural stability. This integrated adsorption-oxidation approach enhances overall treatment efficiency while reducing the electrochemical load on the anode.

Discussion

Mechanistic Understanding of Dual-Function Anode Performance:

The dual-function performance of nanostructured anodes arises from the integration of catalytic and protective functionalities at the material level. The TiO_2-NTs/SnO_2-Sb-PTFE system exemplifies this synergy: the hydrophobic PTFE layer simultaneously promotes •OH release into solution and inhibits anodic dissolution. This dual effect is rooted in the surface chemistry: the hydrophobic surface repels water molecules near the electrode surface, creating a favorable environment for •OH radical generation while minimizing water clustering that would promote oxygen evolution. Simultaneously, the PTFE barrier physically separates the SnO_2 catalytic layer from the electrolyte, reducing the rate of Sn ion dissolution.

The corrosion protection mechanism is multifaceted. In chloride-rich environments, the primary challenge is the competitive chloride oxidation reaction (COR), which generates corrosive species and reduces Faradaic efficiency. Anti-corrosion strategies address this through: (1) designing selective oxygen evolution reaction (OER) active sites that favor water oxidation over chloride oxidation; (2) creating anion exclusion layers that repel chloride ions from the electrode surface; and (3) modifying the electronic structure distribution through elemental doping to alter adsorption energetics. These strategies, initially developed for seawater electrolysis, are directly applicable to dual-function anodes for wastewater treatment where chloride ions are commonly present.

The stability of the electrode-electrolyte interface is critical for long-term dual-function performance. The high OEP of TiO_2-NTs/SnO_2-Sb-PTFE electrodes (2.4 V) inhibits oxygen evolution, reducing local H^+ generation at the anode surface. This is important because low pH promotes SnO_2

dissolution. The presence of PTFE further reduces Sn leaching by limiting electrolyte contact with the SnO_2 layer, particularly in acidic environments where dissolution is most rapid.

Performance Trade-Offs and Optimization Challenges:

The optimization of dual-function anodes involves balancing competing requirements. Higher PTFE loading enhances hydrophobicity and corrosion resistance but may reduce the active surface area available for pollutant oxidation. The observed optimal PTFE loading (4.5 mL/L) reflects this trade-off: at higher loadings (13.5 mL/L), while Sn leaching is further reduced, TOC removal efficiency decreases.

Similarly, noble metal coatings provide exceptional corrosion resistance but introduce significant cost and sustainability concerns. Iridium-coated titanium anodes achieve service lives of 2-5 years but require expensive noble metal catalysts. The development of cost-effective alternatives such as conductive polymer coatings or transition metal-based catalysts addresses this limitation, though often with some sacrifice in absolute performance. PANI-modified anodes achieve corrosion inhibition of approximately 35%, substantially lower than noble metal coatings, but at significantly reduced cost.

The dual-function concept also involves balancing pollutant degradation efficiency with electrode stability. Conditions that favor rapid pollutant oxidation high current density, acidic pH, elevated temperature often accelerate electrode degradation. The development of stable nanostructured architectures, such as TiO_2 nanotubes as substrates for catalytic coatings, improves mechanical stability and resistance to detachment, partially mitigating this trade-off. The TiO_2-NT structure provides a high-surface-area support with strong adhesion to the catalytic layer, reducing catalyst loss under high-current operation.

Long-Term Stability and Service Life Considerations:

Long-term stability remains the critical barrier to the widespread adoption of dual-function anodes in industrial wastewater treatment. Electrochemical stability and longer life are major concerns in EAOPs, and determination of electrode lifetime is essential for practical application. Factors affecting electrode stability include the structural properties of the electrodes, calcination temperature, applied current, and electrical resistance. Electrodes composed of intermediate compounds exhibit higher lifetime than binary oxides, as the presence of multiple oxide components enhances structural integrity and corrosion resistance.

The electrode architecture plays a significant role in stability. Expanded mesh style anodes with polygonised structures better control bubble growth, reducing the negative effects of high pressure on the electrode surface. Anodes with irregular shapes at the surface are more likely to discharge bubbles and reduce pressure-related damage. These geometric considerations are particularly important for long-term industrial operation where bubble formation and gas accumulation can accelerate electrode degradation.

The trade-off between oxidation strength and stability is notable: electrodes having high oxidation strength often have shorter service life values. This reflects the fundamental conflict between high catalytic activity (requiring reactive, often metastable surface states) and long-term stability (requiring chemically robust, often less reactive surfaces). Dual-function anode design addresses this through hierarchical architectures where the catalytic surface provides activity while underlying layers provide structural and chemical stability.

Environmental and Economic Implications:

The dual-function anode approach offers substantial environmental and economic benefits. By extending electrode service life, it reduces the frequency of electrode replacement, decreasing material consumption and waste generation. The reduction in Sn ion leaching minimizes secondary pollution, addressing a significant concern with SnO_2-based electrodes. The efficient pollutant degradation reduces the environmental burden of POPs, while the integrated corrosion protection eliminates the need for separate corrosion inhibitors in the treatment system.

The economic implications are equally significant. The service life extension achieved through PTFE modification, noble metal coatings, or conductive polymer barriers directly reduces capital and operating costs. For TiO_2-NTs/SnO_2-Sb-PTFE electrodes, the reduced Sn leaching translates to longer electrode lifetimes, lower replacement frequency, and reduced maintenance costs. For PANI-modified anodes, the corrosion inhibition efficiency of approximately 35% after repeated cycles reduces iron plate consumption and operating costs.

The scalability of these technologies is an important consideration for industrial adoption. While laboratory-scale demonstrations of TiO_2-NTs/SnO_2-Sb-PTFE electrodes show excellent performance, the translation to large-scale industrial anodes presents challenges in fabrication uniformity, coating adhesion, and long-term performance validation. The development of scalable synthesis methods such as pulse electrodeposition for PTFE incorporation and industrial-scale coating processes

for noble metal anodes is essential for widespread deployment.

Future Directions and Recommendations:

Future research and development should prioritize several interconnected areas to advance dual-function anode technology. First, mechanistic understanding of the interaction between pollutant degradation and corrosion protection at the electrode surface requires further investigation through in-situ characterization techniques and computational modeling. Second, novel nanostructured architectures combining multiple functional components such as core-shell structures, gradient coatings, and hierarchical porosity offer opportunities for enhanced performance.

Third, the development of scalable synthesis methods for dual-function anodes is essential for industrial adoption. This includes continuous coating processes, roll-to-roll fabrication for flexible substrates, and automated quality control systems. Fourth, standardized testing protocols and performance metrics for dual-function anodes established to enable meaningful comparison across studies and facilitate regulatory approval.

Fifth, life-cycle assessment conducted to evaluate the overall environmental and economic benefits of dual-function anodes compared to conventional approaches. Sixth, the integration of dual-function anodes with other treatment processes such as membrane filtration, biological treatment, and adsorption could provide comprehensive wastewater treatment solutions.

Conclusion

This comprehensive review has systematically examined dual-function nanostructured anodes for simultaneous electrochemical degradation of organic pollutants and in-situ corrosion protection of metallic substrates. TiO_2-NTs/SnO_2-Sb-PTFE electrodes demonstrate remarkable performance: oxygen evolution potential of 2.4 V vs Ag/AgCl, TOC removal efficiency of 82% for phenol, and significant reduction in Sn ion leaching compared to conventional electrodes. The hydrophobic surface modification promotes effective release of free hydroxyl radicals into the solution while the PTFE layer acts as a barrier inhibiting anodic dissolution.

Anti-corrosion design strategies for anodes in aggressive environments including selective OER active sites, anion exclusion layers, and electronic structure redistribution offer valuable principles for dual-function electrode design. Iridium-coated titanium anodes achieve service lives of 2-5 years with iridium loss below 0.1 mg/cm²/year, while PANI-modified iron anodes provide corrosion inhibition of approximately 35% after repeated treatment cycles. The dual-function concept integrates catalytic activity for pollutant degradation with corrosion protection, addressing two critical challenges in electrochemical wastewater treatment. Despite substantial progress, challenges persist in optimizing the balance between catalytic activity and corrosion resistance, scaling fabrication for industrial application, and validating long-term performance under realistic conditions. Future research must prioritize mechanistic understanding through advanced characterization, scalable synthesis methods, standardized testing protocols, and life-cycle assessment. With continued innovation, dual-function nanostructured anodes offer transformative potential for sustainable wastewater treatment, combining efficient pollutant removal with extended electrode service life.

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Authors' Contributions

All authors contributed to data analysis, drafting, and revising of the paper and agreed to be responsible for all the aspects of this work.

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