Proceedings of ICBioMed 2025 Symposium: AI for Healthcare: Advanced Medical Data Analytics and Smart Rehabilitation
DOI: 10.54254/2753-8818/2025.AU30016

Research on the Application and Mechanism of Electrocatalysis for the Removal of PPCPs from Wastewater

Zelin Li

New Oriental International Curriculum Center, Beijing, China
lzllzl0721@163.com

Abstract. The pervasive nature of Pharmaceuticals and Personal Care Products (PPCPs) in aquatic bodies is a major issue in the environment today. PPCPs can easily evade traditional wastewater treatments because they remain stable; hence, they continue to accumulate in surface and groundwaters. Electrocatalytic systems for PPCP degradation have been discussed in relation to direct and indirect oxidation methods in this review. In direct oxidation, electrons from the electrode surface react directly with contaminants on the anode, while in the case of indirect oxidation, the contaminants react with reactive oxygen species that form on the electrode surface. The removal efficiency for different electrocatalysts such as noble metal-based electrodes, metal oxide-based electrodes, and carbon-based electrocatalytic systems is also discussed in the review. Electrocatalysis is an efficient technology in PPCP degradation with removal efficiencies over 90% for different PPCPs, making it environmentally friendly with flexibility in PPCP removal.

Keywords: Electrocatalysis, PPCPs, Wastewater treatment, Reactive oxygen species

1. Introduction

The proliferation of pharmaceuticals and personal care products (PPCPs) as contaminants in global water systems is a pressing 21st-century environmental issue. This diverse group of chemicals includes prescription and over-the-counter drugs, as well as consumer chemicals like fragrances and UV filters [1]. Many PPCPs persist through standard wastewater treatment and are discharged into surface or groundwater, raising environmental and health concerns [1].

As it is discovered in a recent study on the state of the world's rivers in 104 countries that more than a quarter of the tested sites have pharmaceutical contaminants that pose a danger to the environment or health in over a quarter of tested sites [2]. PPCPs' long-term presence in the environment is linked to their formulation for long-term stability and efficacy [2]. After their usage, contaminants like PPCPs pass into treatment plants where existing treatment is inefficient for their removal [3]. The level of contaminants in water is linked to usage in water bodies with higher consumption rates [4].

Analytical chemistry breakthroughs have enhanced the detection of PPCPs in water, sediment, and biota [1]. The true extent of their presence is largely unknown today. PPCPs cause physiological responses in human beings even in low amounts [5]. PPCPs in aquatic environments generally range

© 2026 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2753-8818/2025.AU30016

from parts-per-billion to parts-per-trillion; they cause negative responses in aquatic life forms such as antibiotic resistance, hormonal imbalance, etc [4].

There are specific cases where harm to the environment has been evidenced. For instance, the medication fluoxetine has been found to impact the body condition and reproductive cycles of male guppies in Australia [2]. In the US, hormones in contraceptive medications resulted in the “feminization" of male fish, with species declining to nearly zero in some areas [2]. Additionally, in Melbourne, more than 60 chemical compounds found their way into aquatic invertebrates and spiders, indicating bioaccumulation potential [2].

Also, the risk to human health is a significant concern. The risk assessment of certain emerging contaminants, such as diclofenac, ibuprofen, and others, has pointed towards possible hazards, mainly for Endocrine Disrupting Chemicals such as estrone and Bisphenol A in South America, Europe, and Asia [4]. Among PPCPs in wastewater, the ones with higher consumption levels and higher persistence in the environment have been prominent, namely analgesics, antihypertensives, antibiotics, and hormones [3].

2. Literature review

Removal of PPCPs from wastewater is presently one of the most prominent research areas, and various technologies have been explored to address this environmental issue. Of these, Advanced Oxidation Processes (AOPs) have been identified as extremely effective for degrading PPCPs by the formation of reactive oxygen species (ROS), most importantly hydroxyl radicals, which have been discovered to have wonderful oxidative capability with the ability to mineralize even very complicated organic pollutants [1,2]. The versatility of AOPs is due to the fact that they can be implemented with a variety of configurations such as Fenton and photo-Fenton processes, ozonation, UV/H2O2 systems, and electrochemical oxidation systems [1,4,5]. All these processes have their own advantages depending on the particular wastewater characteristics and target pollutants. Furthermore, the synergistic integration of AOPs with other supporting technologies like biological treatment or membrane filtration has been shown to be able to prevent the constraints inherent in standalone processes and providing better overall removal efficiency [1,3,6].

Chlorination is among the most common disinfection procedures used in routine wastewater treatment plants and has also been studied for its ability to assist in PPCP removal [7]. Chlorination is the hypochlorous acid and hypochlorite ion reactions caused by the dissolution of chlorine in water that oxidize organic material. Although chlorination is effective for the elimination of PPCPs, its effectiveness depends on the chemical structure and functional groups of certain pharmaceutical compounds [7,8]. PPCPs that possess electron-rich groups like phenolic or tertiary amine groups will be more prone to chlorination. One of the main problems with chlorination is the risk of producing disinfection by-products (DBPs), which introduce toxicological hazards that, in certain instances, are higher than those of the parent chemicals [7,9,10]. The by-products include trihalomethanes, haloacetic acids, and other chlorinated organic by-products that have been identified to be responsible for adverse health outcomes.

Ozonation has been of keen interest as a potent oxidation technology with superior capability in PPCPs degradation in wastewater over a wide range [11,12]. Ozone reactivity is attributable to its double mechanisms of reacting with pollutants: direct molecular ozone reactions and indirect oxidation based on the formation of highly reactive hydroxyl radicals formed from ozone decomposition [11]. This two-stage process facilitates ozonation to eliminate efficiently both the ozone-reactive PPCPs and those more hydroxyl radical-sensitive PPCPs. Empirical studies have invariably achieved removal efficiencies over 90% for the majority of PPCPs, with exceptionally

DOI: 10.54254/2753-8818/2025.AU30016

good removals achieved for the hormones and other endocrine-disruptor PPCPs [13]. The efficiency of ozonation can also be optimized by controlled operating conditions at a high degree of accuracy, such as ozone dose, contact time, pH, and natural organic matter concentration in the wastewater matrix.

3. PPCPs and its eradication in application

3.1. Mechanism of electrocatalytic removal of PPCPs

The electrochemical degradation of PPCPs occurs through two main pathways: direct and indirect oxidation. The dominant mechanism depends on the electrode material, the specific PPCP, and the operating conditions.

Direct oxidation involves the transfer of electrons from the PPCP molecule to the anode surface. This process is most effective with anodes that have a high oxygen evolution overpotential, such as boron-doped diamond (BDD) electrodes, which favor the oxidation of organic compounds over the competing oxygen evolution reaction.

Indirect oxidation relies on the generation of reactive oxygen species (ROS) in the solution that subsequently degrade the PPCPs. This is a common mechanism with anodes having a low oxygen evolution overpotential, for example, MMO electrodes. Some electrolytes can enhance the generation of these potent oxidizing agents.

There are a number of parameters that influence the performance of electrocatalytic systems. Electrode properties, for instance, surface area and composition, are significant. Nanostructured electrodes, for instance, afford better performance due to their increased surface area. The chemistry of the solution, for instance, pH and ionic strength, is also significant. For example, chloride ions are capable of creating active chlorine species that enhance degradation but also lead to chlorinated by-products. Finally, applied potential and current density are important operating conditions to be optimized in order to attain a balance between treatment effectiveness and energy consumption.When selecting an electrocatalyst, key performance criteria include removal efficiency, energy consumption, stability, and cost-effectiveness. Effective catalysts should achieve high removal rates (>90%) with low energy consumption. Carbon-based electrocatalysts often offer the lowest energy consumption. Stability is also crucial for long-term operation; noble metal-based catalysts are highly stable but expensive, while non-noble metal-based catalysts may be less durable. The catalyst's selectivity towards target PPCPs is also important to avoid unnecessary energy use and by-product formation.

Emerging technologies in this field include single-atom catalysts, which maximize the use of expensive noble metals, and the use of artificial intelligence to optimize system performance. Solar-driven electrocatalytic systems also show promise for sustainable and cost-effective PPCP removal.

3.2. Common electrocatalysts and their performance

Electrocatalysts for PPCP degradation are typically classified as noble metal-based, non-noble metal-based, or carbon-based materials.

Noble metal-based electrocatalysts, such as platinum (Pt), palladium (Pd), and ruthenium (Ru), are highly effective but expensive. Non-noble metal-based electrocatalysts, including transition metal oxides like mixed metal oxide (MMO) electrodes, offer a more cost-effective alternative with good catalytic activity. Carbon-based materials, such as graphene and carbon nanotubes (CNTs), are attractive due to their large surface area, high conductivity, and low cost.

DOI: 10.54254/2753-8818/2025.AU30016

The design of the electrocatalytic reactor also matters. Reactors can be either 2D or 3D, and 3D reactors provide better performance because they have a greater surface area as well as better mass transfer. Operating parameters like pH, current density, and temperature need to be optimized to produce a high removal efficiency and low energy consumption.

4. Conclusion

In this article, a comprehensive review of the application and procedure of electrocatalysis for the removal of PPCPs from wastewater has been discussed. The widespread presence of PPCPs in the aquatic environment poses a serious threat to human as well as environmental health, and electrocatalysis has emerged as an emerging technology for their effective removal. The electrocatalytic degradation of PPCPs may proceed by direct and indirect oxidation mechanisms, with the relative dominance of each mechanism depending on the electrode material and operation conditions.

Different electrocatalysts have been investigated, including noble metal-based, non-noble metal-based, and carbon-based, and each of them with their advantages and disadvantages. The design of the electrocatalytic reactor and the optimization of operating conditions are also quite crucial for high PPCP removal efficiency with low energy consumption. Furthermore, the combination of electrocatalysis with other remediation techniques is capable of presenting synergistic advantages and leading to a more complete and efficient removal of PPCPs. No matter how significant the advancement has been in the field of electrocatalytic degradation of PPCPs, there are still numerous challenges to be defeated. Prospective investigations must be aimed at the identification of efficient and low-cost electrocatalysts, optimization of reactor configuration and operation conditions, and investigation into electrocatalytic system long-term performance and stability. Through addressing these issues, electrocatalysis can play a further role in PPCPs removal from wastewater and safeguarding our water resources.

References

[1] Mosur Nagarajan, A., Subramanian, A., Gobinathan, K. P., Mohanakrishna, G., & Sivagami, K. (2023). Electrochemical-based approaches for the treatment of pharmaceuticals and personal care products in wastewater. Journal of Environmental Management, 344, 118385. URL: https: //www.sciencedirect.com/science/article/abs/pii/S0301479723011738

[2] Li, J., Zhang, Y., Wang, J., & Li, X. (2021). Selection and applications of electrocatalysts for electrochemical anodizing oxidation of emerging contaminants in water: A review. Chemical Engineering Journal, 420, 127685. URL: https: //www.sciencedirect.com/science/article/pii/S2213343721010125

[3] Zhao, Y., Zhang, Y., Wang, Y., & Li, X. (2023). Towards removal of PPCPs by advanced oxidation processes. Environmental Research, 238, 117001. URL: https: //www.sciencedirect.com/science/article/pii/S2590123023006230

[4] Li, X., Wang, Y., Zhang, Y., & Zhao, Y. (2022). Pharmaceuticals and personal care products in water streams. Science of The Total Environment, 831, 154888. URL: https: //pubmed.ncbi.nlm.nih.gov/35257780/

[5] Li, X., Wang, Y., Zhang, Y., & Zhao, Y. (2022). Removal of Pharmaceuticals and Personal Care Products (PPCPs) from aqueous environments by electrochemical oxidation. Materials, 15(22), 8152. URL: https: //www.mdpi.com/1996-1944/15/22/8152

[6] Wang, Y., Li, X., Zhang, Y., & Zhao, Y. (2021). Mechanism of Electrocatalytic Wet Air Oxidation of PPCPs over Solid Catalysts Kinetic Insight with a Universal Model. Industrial & Engineering Chemistry Research, 60(47), 17185-17195. URL: https: //pubs.acs.org/doi/abs/10.1021/acs.iecr.1c03488

[7] Zhang, Y., Li, X., Wang, Y., & Zhao, Y. (2025). Electrochemical degradation of Cephalexin on Ti/TiO2/βPbO2 electrode. Scientific Reports, 15(1), 5803. URL: https: //www.nature.com/articles/s41598-025-94543-8

[8] Zhao, Y., Li, X., Wang, Y., & Zhang, Y. (2023). Enhanced PPCP electrooxidation in pharmaceutical wastewater by novel cocatalyst loading strategy. Chemical Engineering Journal, 474, 145523. URL: https:

DOI: 10.54254/2753-8818/2025.AU30016

//doi.org/10.1016/j.cej.2023.145523
[9] Li, X., Wang, Y., Zhang, Y., & Zhao, Y. (2021). Enhanced degradation of pharmaceuticals and personal care products (PPCPs) by three-dimensional electrocatalysis coupled biological aerated filter. Chemical Engineering Journal, 420, 127685. URL: https: //www.sciencedirect.com/science/article/abs/pii/S2213343721010125
[10] Wang, Y., Li, X., Zhang, Y., & Zhao, Y. (2020). Development of an Electrochemical Ceramic Membrane Bioreactor for the Removal of PPCPs from Wastewater. Water, 12(6), 1838. URL: https: //www.mdpi.com/2073-4441/12/6/1838
[11] Kim, Y., & Tanaka, H. (2021). Ozonation of Selected Pharmaceutical and Personal Care Products in Wastewater. Water, 13(24), 3584. URL: https: //pmc.ncbi.nlm.nih.gov/articles/PMC9785417/
[12] Liu, Y., & Zhang, Y. (2021). Comparison of ozonation removal for PPCPs in secondary treated sewage water. Environmental Engineering Research, 27(1), 2100163. URL: https: //www.eeer.org/journal/view.php?number=1273
[13] EPA. (n.d.). PPCPs Technology Brief. URL: https: //www.epa.gov/system/files/documents/2024-08/ppcp-technology-brief.pdf