

Emerging Technologies for Antibiotic Removal

Ulaganathan Arisekar

Department of Fish Quality Assurance & Management
Fisheries College and Research Institute
Tamil Nadu Dr. J. Jayalalithaa Fisheries University
Thoothukudi – 628 008, Tamil Nadu, India

 Open Access

Abstract

Emerging technologies for antibiotic removal from wastewater are becoming crucial in addressing the growing concern of environmental and pharmaceutical contamination, which contributes to antibiotic resistance and poses a risk to public health. Traditional wastewater treatment methods are often ineffective in removing trace amounts of antibiotics, necessitating the development of innovative solutions. Among these, electrochemical methods, such as electrocoagulation, electrooxidation, and electrochemical advanced oxidation processes (EAOPs), have shown potential by utilizing electric currents to degrade or remove antibiotics through oxidation reactions, generating reactive species that break down contaminants. Membrane technologies, including reverse osmosis, nanofiltration, and membrane bioreactors, offer efficient filtration techniques that selectively remove antibiotics based on their size and charge, providing high-quality treated water. Additionally, by leveraging naturally occurring or engineered enzymes, enzymatic degradation offers a selective, energy-efficient approach that breaks

down complex antibiotics and structures into harmless by-products. AI-driven optimization further enhances these technologies by enabling real-time monitoring and adaptive control of the treatment processes, improving efficiency, and reducing operational costs.

Introduction

Antibiotics, one of the most important medical advancements in the 20th century, have also become a significant environmental concern. Residual antibiotics from pharmaceutical industries, hospitals, and households are seeping into water systems, creating a global challenge: antibiotic pollution. These contaminants threaten aquatic ecosystems and fuel the rise of antibiotic-resistant bacteria, leading to a looming public health crisis. However, cutting-edge technologies have emerged to address this issue.

Advanced Oxidation Processes (AOPs)

Clean water is essential for life, yet antibiotics and other stubborn pollutants turn rivers and lakes into chemical soups. Advanced oxidation processes (AOPs) are cutting-edge solutions that harness the power of reactive radicals to



clean up the mess. Advanced Oxidation Processes (AOPs) represent a groundbreaking approach to tackling water pollution by utilizing the extraordinary power of reactive radicals (Kümmerer, K. 2009). These radicals, such as hydroxyl radicals ($\bullet\text{OH}$), are highly reactive molecules capable of breaking down even the most persistent pollutants, including antibiotics and pharmaceutical residues, into harmless substances, such as water and carbon dioxide (Yuan, X., et al. 2020). AOPs employ various methods to generate these radicals, including photocatalysis using UV light, titanium dioxide, ozonation, and UV-hydrogen peroxide systems.

Biochar: The Sustainable Sorbent

Biochar has a significant cost advantage over activated carbon (AC). The production of biochar costs between 0.35 USD/kg and 1.2 USD/kg, which is approximately one-sixth of the cost of activated carbon. Another interesting property of biochar is its high affinity for the adsorption of organic pollutants. These properties of biochar suggest its use for removing antibiotics from wastewater. The favorable cost of biochar and its promising adsorption properties have led to its increased use to remove antibiotics (Gao et al., 2014). Biochars show selectivity in the adsorption of antibiotics; for instance, they show higher sulfamethoxazole removal capacities than multiwalled carbon nanotubes, graphite, and clay minerals. The adsorption properties were compared based on the adsorption coefficient values, which showed

the partitioning of antibiotics between the adsorbent and the water. This result is interesting because biochar adsorbs higher amounts of sulfamethoxazole antibiotics than carbonaceous adsorbents with low specific surface areas, such as graphite ($1\text{--}10\text{ m}^2/\text{g}$) and multiwalled carbon nanotubes ($100\text{--}1000\text{ m}^2/\text{g}$).

Membrane Technologies: Filtering the Future

Membrane-based separation technologies such as reverse osmosis, nanofiltration, and forward osmosis are at the forefront of antibiotic removal. Recent advances have included hybrid membranes embedded with nanoparticles or polymers that selectively filter antibiotics while maintaining high water recovery rates. With its fine pore size, reverse osmosis can effectively reject a wide range of antibiotics, whereas nanofiltration offers a more energy-efficient option for selectively removing specific antibiotic classes (Zhao et al., 2021). Ultrafiltration, though typically used for larger contaminants, can remove particulates and some antibiotic residues, whereas membrane bioreactors combine biological treatment with membrane filtration, further enhancing the breakdown of antibiotics.

Enzymatic Degradation: Nature's Toolkit

Enzymes capable of breaking down antibiotics have been bioengineered for water-treatment applications. For instance, laccases and peroxidases show promise for degrading antibiotics into non-toxic components. This



nature-inspired solution is efficient and minimizes chemical usage in treatment plants. The key advantage of enzymatic degradation is its ability to selectively degrade various antibiotics, including complex compounds that are resistant to conventional treatments. Enzymes such as laccases, peroxidases, oxidases, and hydrolases have shown the potential to degrade different classes of antibiotics, such as β -lactams, tetracyclines, and fluoroquinolones, by cleaving the chemical bonds in their structures

Microbial Fuel Cells (MFCs): Generating Energy While Cleaning Water

Microbial Fuel Cells leverage bacteria's metabolic activities to break down organic pollutants, including antibiotics, while generating electricity. This dual-purpose technology is a step toward sustainable wastewater treatment. Organic contaminants include wastewater, pollutants, and fuel bacteria in the anode chamber (Cao et al., 2018). As bacteria digest these contaminants, they release electrons that flow through an external circuit to the cathode. This generates an electric current that can be captured and used as an energy source.

Electrochemical Methods: Sparking a Clean Future

Electrochemical oxidation and reduction methods are gaining attention because they can degrade antibiotics without adding external chemicals. Innovations like electrode materials made of boron-doped diamond or graphene enhance efficiency and

reduce energy costs. Electrochemical methods offer an exciting and clean future for removing antibiotics from wastewaters. They are lovely because of their ability to degrade various pollutants, including antibiotics, while potentially generating valuable by-products, such as energy. However, ongoing research and technological developments are necessary to make these methods more efficient, scalable, and cost-effective for widespread use in environmental cleanup.

AI-Driven Optimization in Treatment Plants

Artificial Intelligence (AI) has revolutionized how treatment plants address antibiotic pollution. Machine learning models predict antibiotic concentrations and optimize treatment processes in real time, reducing costs and improving efficiency. I-driven optimization in treatment plants represents a transformative approach for improving the efficiency and effectiveness of antibiotic removal from wastewater. By leveraging advanced machine learning algorithms, AI can analyze complex data from various sensors and monitoring systems in real time to predict the behavior of contaminants, optimize treatment processes, and enhance decision-making. In antibiotic removal, AI can help fine-tune parameters, such as chemical dosing, reaction times, and energy consumption, ensuring that antibiotics are efficiently broken down or removed without overusing resources.

Conclusion

Emerging technologies for antibiotic removal from wastewater represent a promising



and multifaceted approach to addressing the pressing environmental and public health challenges of pharmaceutical contamination. Electrochemical methods, membrane technologies, and enzymatic degradation offer unique advantages for efficiently degrading or removing antibiotics from wastewater. Electrochemical processes harness the power of electric currents to break down contaminants, whereas membrane filtration systems provide selective, high-efficiency removal. Enzymatic degradation, on the other hand, leverages natural catalysts to degrade antibiotics in an eco-friendly and sustainable manner. The integration of AI-driven optimization further enhances these technologies by enabling real-time monitoring and adaptive control, thereby ensuring more efficient and cost-effective treatment. Together, these innovative solutions offer a sustainable, scalable, and efficient means of antibiotic removal, addressing the limitations of traditional methods and contributing to a cleaner, healthier environment

References

- Kümmerer, K., 2009. Antibiotics in the aquatic environment—a review—part I. *Chemosphere*, 75(4), pp.417-434.2. Yuan, X., et al. (2020). "Advanced oxidation processes (AOPs) for the removal of antibiotics from wastewater: A critical review." *Science of the Total Environment*, 715, 136975.
- Liu, T., Aniagor, C.O., Ejimofor, M.I., Menkiti, M.C., Tang, K.H.D., Chin, B.L.F., Chan, Y.H., Yiin, C.L., Cheah, K.W., Chai, Y.H. and Lock, S.S.M., 2023. Technologies for removing pharmaceuticals and personal care products (PPCPs) from aqueous solutions: Recent advances, performances, challenges and recommendations for improvements. *Journal of Molecular Liquids*, 374, p.121144.
- Yang, X.L., Wang, Q., Li, T., Xu, H. and Song, H.L., 2022. Antibiotic removal and antibiotic resistance genes fate by regulating bioelectrochemical characteristics in microbial fuel cells. *Bioresource technology*, 348, p.126752.