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INDEPENDENT SCIENTIFIC ANALYSIS. (Of the article "Electrochemical Treatment of Industrial Wastewater: A Comprehensive Analytical Review and Conceptual Evaluation")

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Abstract

The article presents a novel electrochemical technology for wastewater treatment based on volumetric permeable electrodes operating in a flow-through regime. The proposed system enables controlled modification of water properties, including pH adjustment and microbial inactivation.

The study introduces a modular reactor design based on chemically stable materials and highlights the integration of non-contact monitoring systems using electromagnetic resonance spectroscopy. The approach is evaluated in the context of modern electrochemical water treatment methods, including advanced oxidation processes and hybrid systems (Brillas & Garcia-Segura, 2025; Ganiyu et al., 2020).

The technology is presented as a cost-effective and scalable alternative to existing electrochemical treatment methods.

Keywords: *electrochemical wastewater treatment; volumetric electrochemical reactors; permeable electrodes; flow-through systems; three-dimensional (3D) electrodes; advanced oxidation processes (EAOPs); electro-Fenton; reactive electrochemical membranes (REM); non-contact sensing; electromagnetic resonance spectroscopy; real-time monitoring; sustainable water treatment; decentralized water systems; modular reactor design*

Statement of Independence

I confirm that I am an independent expert in the relevant field and that I do not have any personal, financial, or professional relationships with the author of the reviewed work. This review is based solely on my professional knowledge, experience, and evaluation of the submitted article.

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3. General Information about the Article

The article by Vladyslav Meleshko, entitled “Electrochemical Treatment of Industrial Wastewater”, is devoted to the development and analysis of an original electrochemical approach for water and wastewater treatment.

The work lies at the intersection of electrochemistry, environmental engineering, and water treatment technologies, addressing current challenges in sustainable water purification. The proposed system is based on the flow-through treatment of water passing through volumetric permeable electrodes made of chemically resistant non-metallic materials, enabling controlled modification of physicochemical parameters such as pH and microbiological activity.

The study demonstrates a strong applied orientation and proposes a versatile technological solution suitable for multiple sectors, including agriculture, medicine, and industrial processing.

4. Relevance and Research Context

The global demand for clean water continues to increase due to industrialization, population growth, and the emergence of persistent contaminants such as pharmaceuticals and micro-pollutants. Conventional water treatment technologies often fail to completely remove such contaminants or generate harmful by-products (Oturan & Aaron, 2014).

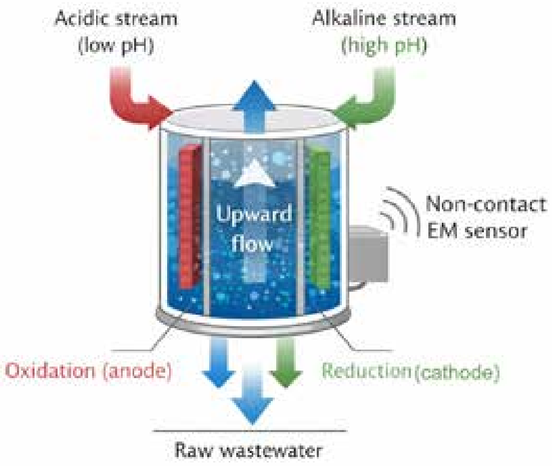
Electrochemical advanced oxidation processes (EAOPs) have emerged as promising solutions due to their ability to generate highly reactive species such as hydroxyl radicals (•OH), which enable effective degradation of organic pollutants (Ganiyu et al., 2020). However, existing systems, including boron-doped diamond (BDD) electrodes and reactive electrochemical membranes (REM), are often limited by high cost, operational complexity, and scalability challenges (Panizza & Cerisola, 2009; Du et al., 2025).

In this context, the article addresses a highly relevant research problem by proposing a simplified electrochemical system that maintains functional efficiency while reducing structural and economic complexity.

5. System Architecture and Operational Principles

The proposed technology is based on a flow-through electrochemical reactor in which water passes through the internal volume of permeable electrodes optionally separated or structurally organized without functional membrane dependence.

Figure 1. *Conceptual diagram of the volumetric flow-through electrochemical reactor*



The system is characterized by:
- vertical electrode configuration;
- upward flow of liquid;
- controllable residence time;
- use of carbon-based materials;

- symmetric and asymmetric electrode designs for pH regulation.

The system allows for the generation of different types of treated water, including acidic, alkaline, and disinfected water, making it suitable for a wide range of applications.

The conceptual design and operating principles of the proposed electrochemical reactor are presented in Figure 1.

6. Scientific Novelty and Conceptual Contribution

The scientific novelty of the proposed approach lies in several key aspects.

- First, the use of volumetric permeable electrodes establishes a three-dimensional electrochemical reaction environment, directly aligning with emerging trends in reactor design aimed at enhancing surface area and mass transfer efficiency (Rodrigo et al., 2014);
- Second, the implementation of a flow-through regime enables continuous treatment with improved hydrodynamic control, resulting in enhanced mass transfer and overall process efficiency;
- Third, the system provides a simplified alternative to membrane-based technologies, such as reactive electrochemical membranes (REM), by eliminating membrane-associated limitations while preserving the advantages of flow-through operation (Du et al., 2025);
- Fourth, the integration of non-contact sensing based on electromagnetic resonance introduces real-time monitoring capabilities without direct interaction with the treated fluid, addressing a critical limitation of conventional electrochemical systems.

Finally, the development of a flexible and modular system architecture enables scalability and adaptability across a wide range of operational conditions and application domains.

7. Practical Significance and Technology Readiness

The proposed technology demonstrates clear practical relevance by combining low-cost materials, architectural simplicity, and operational flexibility. In contrast to many advanced electrochemical systems that depend on expensive electrodes or complex configurations, this approach relies on carbon-based and polymer components, enabling economically viable deployment across both decentralized and industrial scales.

A defining advantage is the reduction of operational complexity. The use of permeable electrodes and gravity-driven flow eliminates the need for sophisticated control systems and highly specialized personnel, thereby expanding applicability to low-resource and distributed treatment scenarios.

Scalability is inherently supported by a modular reactor design, allowing capacity adjustment without fundamental system redesign. The technology can be deployed as compact local units (50–250 L/h) or integrated into larger treatment infrastructures with minimal capital modification. Compatibility with existing systems further lowers barriers to adoption.

Beyond treatment efficiency, the system introduces functional versatility by generating chemically distinct output streams (acidic, alkaline, and disinfected water), enabling a single platform to perform multiple process roles that are typically separated across different technologies.

The integration of non-contact sensing provides real-time process visibility without exposure to aggressive media, addressing a key limitation of conventional systems lacking reliable monitoring. This capability supports process stability and enables future automation and data-driven control.

Taken together, these features position the technology as a cost-efficient, scalable, and multifunctional platform with strong potential across sectors including water treatment, agriculture, food processing, and high-purity industrial applications. Its capacity to integrate into existing infrastructure while expanding functional performance underscores its relevance for next-generation water treatment systems.

8. Experimental Basis and Theoretical Limitations

The article by Meleshko (2026) provides a conceptual and structural description of the proposed reactor system, outlining its design principles and key operational parameters. However, it does not yet include a comprehensive quantitative characterization of the underlying electrochemical processes.

In contrast, contemporary research in electrochemical water treatment places strong emphasis on the mechanistic and kinetic understanding of system performance. This includes detailed analysis of:

- reactive species generation, particularly hydroxyl radical formation pathways;
- electrochemical reaction kinetics and rate-limiting steps;
- energy efficiency metrics (e.g., kWh/m^3);
- and degradation pathways of target contaminants (Brillas & Garcia-Segura, 2025; Ganiyu et al., 2020).

The absence of such quantitative data in the study by Meleshko (2026) limits the ability to rigorously evaluate process efficiency, benchmark performance against existing technologies, and predict scaling behavior.

Nevertheless, the framework proposed by Meleshko (2026) establishes a solid foundation for further investigation. Future work should focus on integrating electrochemical diagnostics, kinetic modeling, and energy analysis, enabling a transition from qualitative description to quantitatively validated system performance.

9. Positioning within Modern Electrochemical Treatment Technologies

Electrochemical wastewater treatment has rapidly evolved toward highly efficient oxidation systems, including EAOPs, electro-Fenton processes, reactive electrochemical membranes (REM), and photoelectrochemical (PEC) platforms. These approaches achieve high removal efficiencies; however, they remain constrained by critical limitations, including electrode and membrane fouling, narrow operational pH windows, high material costs, and limited integration of real-time monitoring and adaptive control (Brillas & Garcia-Segura, 2025; Oturan & Aaron, 2014; Ganiyu et al., 2020).

The technology proposed in this article departs from conventional surface-based electrochemical paradigms by employing a volumetric, flow-through electrode architecture, enabling distributed reaction zones and tunable residence time. Coupled with non-contact sensing for in situ monitoring, this approach addresses key bottlenecks in process stability and scalability.

Rather than competing with established systems, the proposed configuration is best understood as a platform for integration, capable of interfacing with and enhancing existing electrochemical and photoelectrochemical processes.

9.1. Reactive Electrochemical Membranes (REM)

To establish a baseline for comparison, the analysis begins with reactive electrochemical membrane (REM) systems, which represent one of the most advanced implementations of flow-through electrochemical treatment.

Reactive electrochemical membranes (REM) represent one of the most rapidly developing directions in electrochemical water treatment, combining filtration and electrochemical oxidation within a single functional unit (Du et al., 2025; Zhu et al., 2023). These systems are characterized by flow-through operation, localized reaction zones, and high current densities, enabling efficient removal of micropollutants.

The proposed technology described in this work exhibits strong conceptual similarities with REM systems, particularly in terms of flow-through architecture and distributed reaction zones. However, a key distinction lies in the absence of functionally loaded membranes. Instead, the system employs permeable, chemically stable non-metallic electrodes, allowing the liquid to pass through the electrode volume.

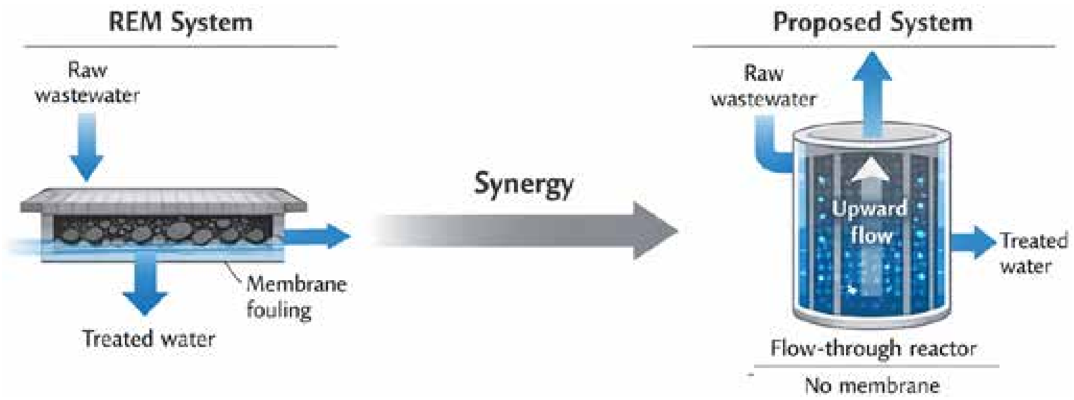
This design eliminates one of the primary limitations of REM systems – membrane fouling, which significantly reduces operational efficiency and increases maintenance requirements (Du et al., 2025).

Potential synergy:

Hybridization of REM selectivity with the volumetric electrode concept proposed here could enable the development of highly efficient and fouling-resistant electrochemical reactors, particularly suitable for selective removal of persistent organic pollutants.

A conceptual comparison between reactive electrochemical membrane systems and the proposed volumetric reactor architecture is presented in Figure 2.

Figure 2. *Comparison of reactive electrochemical membrane systems and a volumetric flow-through electrochemical reactor*



9.2. Electro-Fenton Processes

While REM systems emphasize reactor architecture and mass transfer, electro-Fenton processes provide a complementary perspective focused on the generation of highly reactive oxidative species.

Electro-Fenton processes are widely recognized as one of the most effective advanced oxidation methods due to their ability to generate hydroxyl radicals (•OH) in situ, enabling deep mineralization of organic contaminants (Oturan & Aaron, 2014; Heidari et al., 2023; Li et al., 2025).

The proposed system utilizes carbon-based permeable electrodes, which are highly suitable for electro-Fenton applications due to their ability to catalyze hydrogen peroxide generation at the cathode. Moreover, the volumetric configuration enhances:

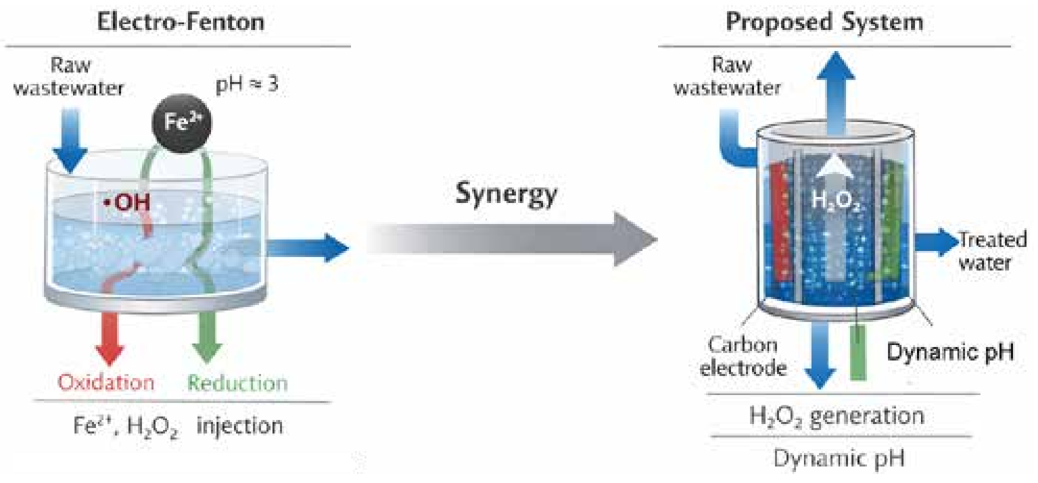
- interfacial area;
- mass transfer;
- and residence time control.

A significant advantage of the proposed technology is its ability to dynamically regulate pH conditions through electrochemical separation, as described in Section 2. This capability addresses a major limitation of conventional electro-Fenton systems, which typically require strictly acidic conditions.

Potential synergy:

Integration of electro-Fenton mechanisms into the proposed reactor design could lead to the development of high-efficiency hybrid oxidation systems, operating under broader pH conditions and reduced energy demand.

Figure 3. *Conceptual integration of electro-Fenton processes with a volumetric electrochemical reactor*



The integration of electro-Fenton mechanisms with the proposed volumetric electrochemical system is illustrated in Figure 3.

9.3. 3D Electrochemical Reactors

Beyond reaction pathways, reactor geometry plays a defining role, making it necessary to consider three-dimensional electrochemical reactors as a structural analogue to the proposed system.

Three-dimensional electrochemical reactors are known for their enhanced performance due to increased active surface area and improved mass transfer (Rodrigo et al., 2014; Ganiyu et al., 2020).

The technology presented in this study inherently corresponds to the concept of a 3D electrochemical reactor, as it involves fluid flow through a permeable electrode volume, rather than along electrode surfaces.

Distinctive features of the proposed approach include:

- gravity-driven upward flow, ensuring stable hydrodynamics;
- controllable residence time, directly influencing reaction kinetics;
- modular design, enabling scalability and flexible implementation.

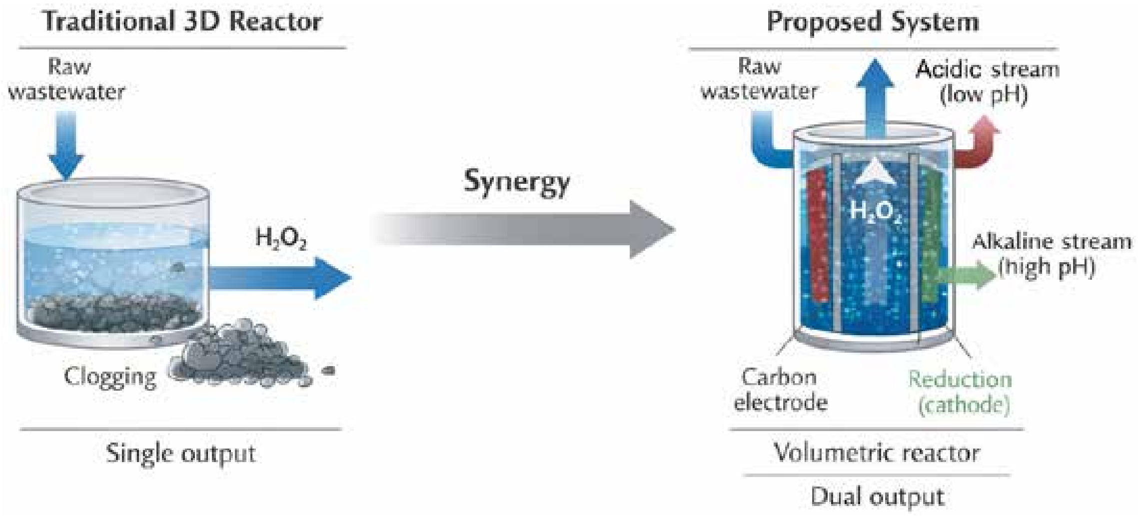
Unlike conventional 3D systems, the proposed configuration also enables simultaneous generation of chemically distinct streams (acidic and alkaline fractions), which expands its functional applicability.

Potential synergy:

Further development could involve the incorporation of catalytic or porous media within the electrode structure to enhance reaction selectivity and efficiency.

A structural comparison between conventional 3D electrochemical reactors and the proposed system is shown in Figure 4.

Figure 4. *Comparison of conventional 3D electrochemical reactors and a volumetric flow-through system*



9.4. Photoelectrochemical Systems (PEC)

Although electrochemical systems dominate the field, photoelectrochemical approaches introduce additional functionality through light-driven processes and highlight challenges in system control and scalability.

Photoelectrochemical (PEC) systems are increasingly considered a promising approach for sustainable wastewater treatment, combining light-driven and electrochemical processes (Dong et al., 2025; Amaya Santos et al., 2025). However, their large-scale implementation remains limited by process instability and the lack of real-time monitoring.

A unique contribution of the proposed system is the integration of a non-contact resonant sensing technology, based on electromagnetic spectroscopy principles. This sensor:

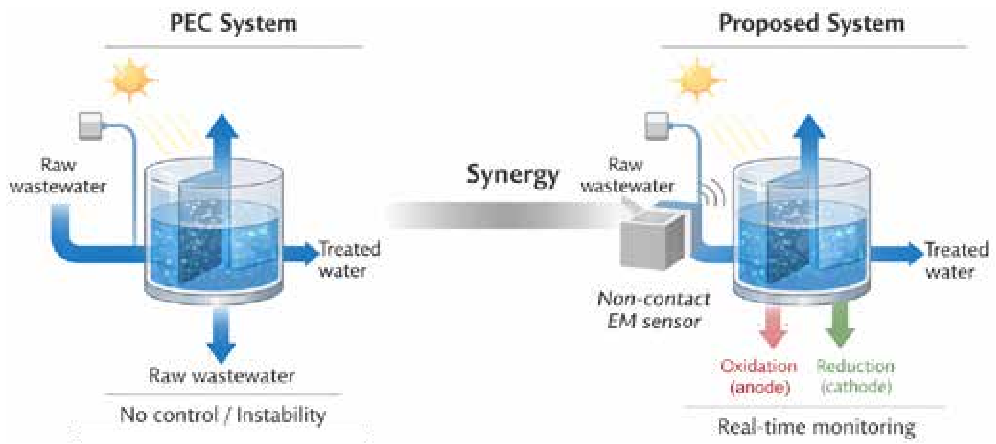
- operates without direct contact with the liquid;
- provides high sensitivity (down to 10^{-6} mg/L);
- enables continuous, real-time monitoring of water composition.

Potential synergy:

Integration of this sensing approach into PEC systems could enable adaptive process control, significantly improving system stability and scalability – two of the major challenges identified in recent PEC research.

The potential enhancement of photoelectrochemical systems through integration of non-contact sensing is illustrated in Figure 5.

Figure 5. *Integration of non-contact sensing into photoelectrochemical systems*



9.5. BDD-Based Systems (Boron-Doped Diamond Electrodes)

At the material level, these considerations naturally lead to a comparison with high-performance electrode systems, particularly those based on boron-doped diamond (BDD).

Boron-doped diamond (BDD) electrodes are considered among the most powerful materials for electrochemical oxidation due to their ability to generate highly reactive species and their exceptional stability (Panizza & Cerisola, 2009; Martínez-Huitle & Brillas, 2009).

Despite their advantages, BDD systems are limited by:

- high production costs;
- complex fabrication processes;
- limited scalability.

In contrast, the proposed system utilizes carbon-based composite electrodes, offering:

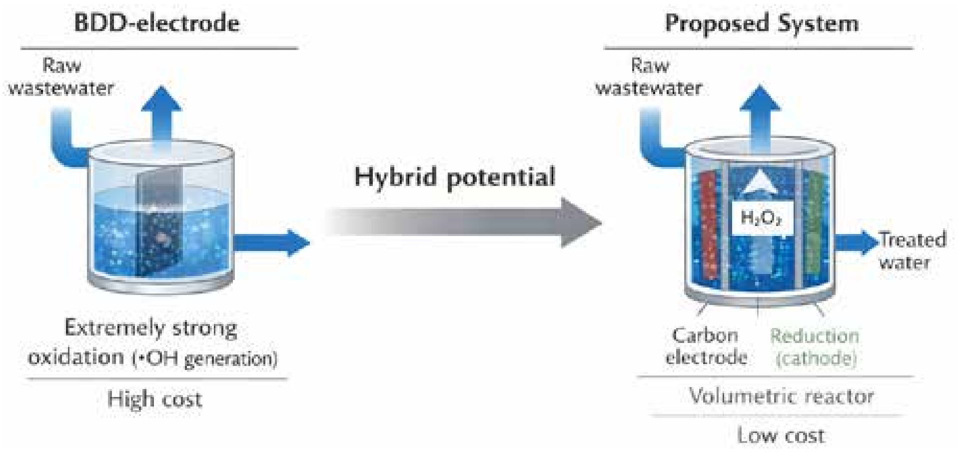
- significantly lower cost;
- chemical stability;
- ease of manufacturing and scaling.

While BDD systems maximize oxidation power at the electrode surface, the proposed technology emphasizes volumetric processing and hydrodynamic optimization, representing a fundamentally different approach.

Potential synergy:

Hybrid systems combining localized BDD electrodes with volumetric carbon-based reactors could provide an optimal balance between performance and cost.

Figure 6. *Comparison of boron-doped diamond electrode systems and a volumetric electrochemical reactor*



A comparison between BDD-based systems and the proposed reactor concept is presented in Figure 6.

Overall Positioning within EAOP Framework

Modern electrochemical advanced oxidation processes (EAOPs) are evolving toward systems that combine high oxidation efficiency, improved mass transfer, reduced energy consumption, and integrated monitoring capabilities (Brillas & Garcia-Segura, 2025; Ganiyu et al., 2020).

Within this framework, the proposed technology can be positioned as a multifunctional platform, integrating:

- volumetric electrochemical treatment (3D reactor concept);
- flexible control of physicochemical parameters (pH, residence time);
- cost-effective electrode materials;
- embedded real-time monitoring.

Rather than competing directly with existing technologies, the system demonstrates strong potential as a hybridization platform, capable of integrating:

- electro-Fenton processes;
- photoelectrochemical systems;
- membrane-based electrochemical reactors;
- anodic oxidation technologies.

Conclusion of Comparative Analysis

The proposed system should not be viewed as a direct alternative to existing electrochemical treatment technologies, but rather as an integrative architecture capable of combining multiple mechanisms within a single framework.

Its key advantage lies in the synergistic combination of:

- electrochemical reactivity;
- volumetric hydrodynamics;
- and advanced sensing capabilities.

This positions the technology as a promising candidate for next-generation water treatment systems, particularly in applications requiring adaptability, scalability, and cost-efficiency.

10. Limitations and Research Gaps

Despite the conceptual strength of the approach proposed by Meleshko (2026), several limitations remain that constrain its current scientific and practical validation.

A primary limitation is the lack of detailed mechanistic analysis. Modern electrochemical treatment research emphasizes the identification of dominant oxidation pathways, including hydroxyl radical (•OH) generation and alternative reactive species formation (Brillas & Garcia-Segura, 2025; Ganiyu et al., 2020). In the absence of such analysis, the fundamental reaction mechanisms governing the proposed system remain insufficiently characterized.

Closely related is the absence of quantitative kinetic data, including reaction rates, current efficiencies, and limiting steps. Without these parameters, it is not possible to establish a rigorous comparison with established electrochemical advanced oxidation processes (EAOPs) or to predict system behavior under varying operational conditions.

Another important gap concerns the formation and fate of by-products. Contemporary studies highlight that incomplete oxidation may lead to the generation of intermediate compounds, some of which can be more toxic than the parent pollutants (Oturan & Aaron, 2014). The lack of by-product analysis limits the assessment of the system's environmental safety and treatment completeness.

The limited discussion of energy consumption further constrains practical evaluation. Energy efficiency, typically expressed in kWh/m³, is a critical parameter in benchmarking electrochemical technologies (Brillas & Garcia-Segura, 2025). Without such data, the economic feasibility and scalability of the system cannot be fully assessed.

Taken together, these limitations do not diminish the conceptual contribution of the work but rather define a clear roadmap for future research, particularly in the direction of quantitative validation, mechanistic elucidation, and pilot-scale implementation.

11. Environmental Significance of the Technology

The technology proposed by Meleshko (2026) demonstrates notable potential in the context of sustainable and environmentally responsible water treatment.

A key advantage is the reduced reliance on chemical reagents, as the system is based on electrochemical processes that generate reactive species in situ. This aligns with current trends in green water treatment technologies, where minimizing secondary chemical inputs is a major objective (Ganiyu et al., 2020).

The system also shows strong potential for decentralized and distributed applications, enabled by its modular design, operational simplicity, and relatively low infrastructure requirements. Such characteristics are particularly important for rural, remote, or resource-limited regions, where centralized treatment systems are often impractical.

From an environmental perspective, the use of carbon-based and polymer materials offers advantages in terms of reduced material toxicity and improved lifecycle sustainability compared to more resource-intensive alternatives such as boron-doped diamond electrodes. Additionally, the absence of membrane components eliminates issues related to membrane disposal and fouling-related waste streams.

The capability to generate functionally distinct water streams (acidic, alkaline, disinfected) further enhances resource efficiency by enabling targeted reuse of treated water across different applications, including sanitation, agriculture, and industrial processes.

Moreover, the integration of non-contact sensing technology supports real-time monitoring and process optimization, which is critical for minimizing energy consumption and preventing over-treatment. Such features are increasingly recognized as essential for the development of intelligent and adaptive water treatment systems (Dong et al., 2025).

In the broader context, technologies of this type contribute to achieving global sustainability objectives, including water reuse, pollution reduction, and resource efficiency, which are central to international environmental frameworks and water management strategies.

The technology is directly aligned with global sustainability frameworks, particularly UN Sustainable Development Goal 6 (Clean Water and Sanitation).

12. Conclusion and Future Outlook

The study presents an innovative and practically oriented approach to electrochemical water treatment. Its simplicity, flexibility, and integration with advanced monitoring technologies position it as a promising candidate for next-generation water treatment systems.

The proposed system should be viewed not as a single-process solution, but as a platform technology capable of integrating multiple electrochemical and hybrid treatment mechanisms. This positioning significantly expands its applicability and aligns it with current trends toward modular, adaptive, and decentralized water treatment systems.

Overall, the technology represents a transition toward more adaptable, scalable, and resource-efficient electrochemical treatment systems, with strong potential for both industrial and decentralized applications.The proposed technology represents a shift from surface-limited electrochemical systems toward volumetric, process-integrated architectures, offering a new direction for scalable and adaptive water treatment.

Its combination of low-cost materials, modular design, and integrated sensing positions it as a viable candidate for next-generation decentralized water treatment systems.

Based on the above analysis, the reviewed article represents a scientifically grounded and practically significant contribution to the field of electrochemical water treatment and demonstrates strong potential for further development and application.

References

Meleshko, V. (2026). Electrochemical Treatment of Industrial Wastewater. Published online at IntellectualArchive.com, March 4, 2026.

Brillas, E., & Garcia-Segura, S. (2025). Electrochemical advanced oxidation processes for real wastewater remediation: Systems, performance, and generated oxidants. ACS Electrochemistry, – 2(1). – 45–68. URL: URL: https://doi.org/10.1021/acselectrochem.5c00311.

Oturan, M. A., & Aaron, J.-J. (2014). Advanced oxidation processes in water/wastewater treatment: Principles and applications. A review. Critical Reviews in Environmental Science and Technology, – 44(23). – P. 2577–2641. URL: https://doi.org/10.1080/10643389.2013.829765.

Heidari, Z., Pelalak, R., & Zhou, M. (2023). Recent progress in electro-Fenton process for wastewater treatment at near-neutral pH: A review. Chemical Engineering Journal, – 468. – 143600 p. URL: https://doi.org/10.1016/j.cej.2023.143600.

Li, X., Zhang, Y., Wang, H., & Chen, G. (2025). Advances in heterogeneous electro-Fenton processes for efficient water treatment. Journal of Hazardous Materials, – 465. – 133210 p. URL: https://doi.org/10.1016/j.jhazmat.2024.133210.

Du, M., Li, W., Zhang, D., & Chen, Z. (2025). Recent advances in electrochemical membrane reactors based on cathodic carbon membranes for water treatment. Journal of Membrane Science, – 712. – 121345 p. URL: https://doi.org/10.1016/j.memsci.2024.121345.

Zhu, Y., Wang, L., & Chen, Z. (2023). Electrochemical anodic oxidation-based membrane systems for micropollutant removal. ACS ES&T Engineering, – 3(4). – P. 1123–1137. URL: https://doi.org/10.1021/acsestengg.3c00179

Dong, T., Li, J., & Wang, S. (2025). Recent advances in oxidant-involved photoelectrochemical systems for sustainable wastewater treatment. Nature Reviews Clean Technology, – 1. – P. 45–67. URL: https://doi.org/10.1038/s44296-025-00084-6.

Amaya Santos, G., Martínez-Huitle, C. A., & Rodrigo, M. A. (2025). Scaling-up photoelectrochemical oxidation processes: From laboratory to industrial applications. Water Research, – 248. – 120715 p. URL: https://doi.org/10.1016/j.watres.2025.120715.

Martínez-Huitle, C. A., & Brillas, E. (2009). Decontamination of wastewaters containing synthetic organic dyes by electrochemical methods: A general review. Applied Catalysis B: Environmental, – 87(3–4). – P. 105–145. URL: https://doi.org/10.1016/j.apcatb.2008.09.017.

Panizza, M., & Cerisola, G. (2009). Direct and mediated anodic oxidation of organic pollutants. Chemical Reviews, – 109(12). – P. 6541–6569. URL: https://doi.org/10.1021/cr9001319.

Rodrigo, M. A., Oturan, N., & Oturan, M. A. (2014). Electrochemically assisted remediation of pesticides in soils and water: A review. Chemical Reviews, – 114(17). – P. 8720–8745. URL: https://doi.org/10.1021/cr5002059.

Ganiyu, S. O., Martínez-Huitle, C. A., & Oturan, M. A. (2020). Electrochemical advanced oxidation processes for wastewater treatment: Advances in formation and detection of reactive species and mechanisms. Current Opinion in Electrochemistry, – 22. – P. 57–64. URL: https://doi.org/10.1016/j.coelec.2020.04.002.

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