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Sustainable Electrochemistry and Environmental Applications

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Abstract
Sustainable electrochemistry offers innovative solutions for addressing environmental challenges through green and efficient electrochemical processes. This paper explores the principles of green chemistry in electrochemical applications, emphasizing atom economy, renewable resources, and energy efficiency. Key areas discussed include electrochemical water treatment, which provides practical solutions for wastewater purification and desalination, and carbon capture and conversion technologies, where CO_2 *is electrochemically reduced to value-added products. Additionally, advancements in renewable energy storage, such as sustainable battery technologies and fuel cells, demonstrate the potential of electrochemical systems in reducing environmental impact. Electrochemical sensors for ecological monitoring further contribute to the real-time detection and management of pollutants, while life cycle assessments ensure sustainable technology development. Despite the potential, challenges remain in scalability and integration. This paper highlights these opportunities and challenges, presenting a comprehensive overview of sustainable electrochemical applications that support environmental conservation.*

Keywords: *sustainable electrochemistry, green chemistry, environmental applications, electrochemical water treatment, carbon capture, renewable energy storage*

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I. Introduction

Sustainable electrochemistry is emerging as a powerful tool to address some of the most pressing environmental challenges we face today, from water and air pollution to renewable energy storage and greenhouse gas emissions. Although widely used in various applications, traditional electrochemical processes often rely on finite resources, generate significant waste, and involve toxic chemicals. As the global demand for energy and resources grows, making electrochemical processes more environmentally friendly has become paramount. By integrating principles of green chemistry, sustainable electrochemistry aims to minimize the ecological footprint of these processes while maximizing their efficiency and versatility in applications across various environmental sectors(Poizot and Dolhem, 2011; Rand, 2011; Yang et al. 2011).Electrochemistry fundamentally involves converting chemical energy into electrical energy and vice versa. This property makes it highly valuable for applications where energy storage, pollutant degradation, or resource recovery is essential. In recent years, materials science and electrochemical engineering advances have enabled more sustainable methods, leading to innovations such as using renewable or biodegradable materials, energy-efficient systems, and catalysts that enhance reaction rates while reducing environmental harm. These developments make sustainable electrochemistry a promising approach to meeting environmental sustainability goals, including climate action, resource efficiency, and pollution control—one of the critical areas where sustainable electrochemistry can significantly impact water treatment and purification. Electrochemical water treatment methods, such as advanced oxidation processes and electrochemical desalination, offer efficient ways to remove contaminants from water without the need for hazardous chemicals. These methods can target specific pollutants, including organic compounds, heavy metals, and pathogens, making them valuable for wastewater treatment and ensuring access to clean water(Larcher and Tarascon, 2015; Badwal et al. 2014; Mohan et al. 2024). In addition to their environmental benefits, electrochemical water treatment technologies are often more cost-effective and adaptable to various contaminants, making them practical solutions for urban and rural settings.Another transformative application of sustainable electrochemistry lies in carbon capture and conversion (CCC), which addresses the critical issue of greenhouse gas emissions. Electrochemical CO_2 reduction, where carbon dioxide is converted into valuable products such as fuels and chemicals, offers a dual benefit: reducing CO_2 emissions and creating economic value. This process helps mitigate climate change and provides an alternative to fossil-based chemicals and fuels. However, the large-scale deployment of CCC technologies requires further research to improve catalyst efficiency and durability, optimize energy use, and make the processes economically viable. With continued advancements, CCC could become a cornerstone in achieving carbon neutrality.Renewable energy storage is also a crucial field in which sustainable electrochemistry plays a vital role. Energy storage technologies, such as batteries and supercapacitors, are essential for integrating renewable energy sources like solar and wind into the grid. Sustainable electrochemistry focuses on developing storage devices that use eco-friendly, abundant materials and have high energy efficiency and long lifespans. New materials and design approaches, such as sodium-ion batteries and biodegradable supercapacitors, are being explored to reduce reliance on scarce and toxic materials, such as cobalt and lead(Chu and Majumdar, 2012; Bhuiyan, 2022; Ganiyu et al. 2020; Poizot et al. 2020). These innovations in energy storage contribute to the reliability of renewable energy systems and promote a circular economy by minimizing waste and enhancing recyclability.Hydrogen production and fuel cells are other vital areas where sustainable electrochemistry is making strides. Hydrogen is a clean energy carrier with significant potential for decarbonizing sectors like transportation and industry. Electrochemical water splitting, a process that produces hydrogen by splitting water into hydrogen and oxygen, becomes sustainable when powered by renewable electricity. Advances in this area focus on developing efficient electrolyzes and reducing the use of precious metals in catalysts. Also, hydrogen fuel cells offer a clean energy solution for vehicles, stationary power, and backup power systems, emitting only water as a byproduct. Sustainable electrochemical innovations in hydrogen production and fuel cells are crucial for achieving a low-carbon energy future.Corrosion prevention and the development of sustainable materials are also vital components of sustainable electrochemistry. Corrosion leads to the degradation of materials and infrastructure, causing environmental and economic issues. Electrochemical methods for corrosion protection, such as cathodic protection and the use of environmentally friendly inhibitors, help prevent corrosion while minimizing toxic substances(Zhang et al. 2024; Hassan et al. 2024; Capurso et al. 2022). Furthermore, developing biodegradable coatings and renewable materials for corrosion resistance supports sustainable infrastructure and reduces the environmental impact of metal extraction and processing.The life cycle assessment (LCA) of electrochemical technologies is increasingly used to evaluate the ecological effects of these processes, from raw material extraction to disposal. By analyzing each stage of an electrochemical technology's life cycle, LCA helps identify areas for improvement and supports implementing circular economy principles. Thisapproach significantly benefits sustainableelectrochemistry, as it encourages the design of technologies with minimal waste generation, efficient recycling, and reduced overall environmental impact.Despite the advancements and potential of sustainable electrochemistry, several challenges remain. Scaling up laboratory discoveries to industrial applications requires overcoming technical and economic barriers, such as the high costs of sustainable materials and the need for robust, efficient catalysts. Integrating sustainable electrochemical processes with existing infrastructure and renewable energy sources also demands further research and collaboration across disciplines. Sustainable electrochemistry offers promising solutions for various environmental issues, from water purification and pollution control to renewable energy storage and carbon management. By adhering to green chemistry principles and leveraging recent advancements in materials science, sustainable electrochemistry mitigates environmental impacts and opens new opportunities for eco-friendly innovations. As research in this field progresses, sustainable electrochemistry is poised to play a critical role in global efforts to create a cleaner, more sustainable future(Guilbert and Vitale, 2021; Kabir et al. 2023; Hosseini and Wahid, 2020).

II. Principles of Green Chemistry in Electrochemical Processes

As global awareness of environmental challenges grows, applying green chemistry principles within electrochemical processes has become more critical than ever. Green chemistry, often called sustainable chemistry, involves designing chemical products and processes to reduce or eliminate hazardous substances, lower waste generation, and enhance energy efficiency. These principles have become foundational in the shift toward sustainable electrochemical applications, enabling advancements in water treatment, renewable energy storage, and carbon capture. Some of the most relevant principles within electrochemistry include atom economy and waste reduction, using renewable resources and non-toxic solvents, and energy efficiency in electrochemical systems.Atom economy is a fundamental principle of green chemistry that seeks to maximize the incorporation of all atoms from starting materials into the final product, thereby minimizing waste. This concept is essential for improving the sustainability of electrochemical processes, and in traditional chemical processes, creating by-products that do not serve any functional purpose results in increased material consumption and waste generation. However, in a high atom economy reaction, nearly all atoms from the reactants are integrated into the desired product, reducing the need for further waste management and disposal, which can be environmentally costly.For example, in the context of electrochemical processes, the efficiency of reactions like water splitting (to produce hydrogen and oxygen) can be optimized to ensure minimal generation of by-products. Waste production is reduced by selecting electrodes and catalysts that specifically target the desired reactions(Koel and Kaljurand, 2019; Ganesh et al. 2021; Gilbertson et al. 2015). This principle can also be applied to electrochemical synthesis, where the atom economy can be maximized by electrocatalysts that enable selective reactions, such as producing only the desired product without side reactions. Electrochemical reactions' selective nature allows researchers to manipulate conditions to optimize the atom economy, ensuring that fewer resources are wasted in unwanted responses.A practical example of this principle can be seen in carbon capture and conversion processes. Electrochemical carbon dioxide (CO_2) reduction involves converting CO_2 into valuable chemicals, such as methanol or ethylene, through selective electrochemical reactions. The process achieves a high atom economy by using catalysts that increase selectivity, as the CO_2 is effectively incorporated into valuable products rather than being emitted as waste. Furthermore, the electrochemical nature of these reactions allows them to be controlled precisely, providing opportunities to optimize for atom economy by adjusting parameters such as electrode material, electrolyte composition, and voltage.Atom economy also plays a significant role in battery technologies. For instance, lithium-ion batteries traditionally require metals such as cobalt, which are limited resources and come with environmental costs related to extraction and processing. By improving atom economy in battery design, researchers are working to reduce reliance on rare metals and maximize the use of abundant materials like iron or sodium. Innovations such as lithium-iron-phosphate and sodium-ion batteries highlight the efforts to achieve higher atom economy in electrochemical energy storage, contributing to the sustainability of battery technology(Zimmerman et al. 2020; Koel and Kaljurand, 2006; Doble et al. 2010).A central goal of sustainable electrochemistry is to reduce reliance on finite or hazardous resources by integrating renewable resources and non-toxic solvents into electrochemical processes. Renewable materials not only conserve natural resources but also contribute to reducing greenhouse gas emissions associated with material extraction and processing. Non-toxic solvents, on the other hand, help minimize health risks and environmental pollution.Electrochemical systems are increasingly exploring using bio-based or recyclable materials for electrodes, membranes, and catalysts. For example, in fuel cell technology, researchers are developing catalysts that use earth-abundant metals, such as iron and manganese, instead of platinum. Platinum, while highly effective as a catalyst, is rare, expensive, and energy-intensive to mine. By substituting platinum with more accessible and renewable materials, fuel cell technology becomes more economically viable and environmentally friendly.In addition, the solvents used in electrochemical processes play a significant role in sustainability. Many traditional solvents used in chemical synthesis are volatile organic compounds (VOCs), which can contribute to air pollution and pose health risks. In green electrochemistry, the emphasis is on replacing these solvents with safer alternatives. Water is a prime candidate, as it is non-toxic, abundant, and an effective solvent for many electrochemical reactions. Ionic liquids, which are salts in liquid form, are also gaining attention as environmentally friendly solvents due to their low volatility and thermal stability. These solvents can improve the efficiency of electrochemical reactions while reducing harmful emissions.In battery technology, renewable resources are also being prioritized(Erythropel et al. 2018; Marion et al. 2017). Traditional batteries often contain toxic materials, such as lead and cadmium, which pose environmental hazards. However, researchers are developing batteries with materials sourced from renewable biomass, like lignin-based carbon electrodes, which are biodegradable and non-toxic. Similarly, bio-based electrolytes are being explored as alternatives to conventional, often hazardous, organic solvents in batteries. By incorporating renewable and non-toxic components, these batteries support sustainable energy storage and offer safer disposal options at the end of their life cycle.Electrochemical water treatment is another area where renewable and non-toxic resources are critical. Conventional water treatment methods can involve harsh chemicals that may leave residues in treated water or produce toxic by-products. Electrochemical methods, however, can utilize simple and non-toxic agents, such as oxygen and water, to produce reactive species (e.g., hydroxyl radicals) that degrade contaminants. These methods are effective and environmentally benign, aligning with green chemistry principles by reducing reliance on hazardous materials.Energy efficiency is a cornerstone of sustainable electrochemistry, particularly as many electrochemical reactions require significant energy inputs. Improving energy efficiency lowers the environmental impact of electrochemical processes and reduces operational costs, making sustainable technologies more accessible and economically viable(Saravanan et al. 2021; Ghernaout et al. 2011). Achieving energy efficiency in electrochemical systems involves optimizing reaction conditions, enhancing catalyst performance, and implementing innovative cell designs that minimize energy loss. Energy efficiency is paramount in applications such as water splitting for hydrogen production. Electrolysis, the process of splitting water into hydrogen and oxygen, requires considerable energy, mainly when traditional materials are used for electrodes and catalysts. Sustainable electrochemistry focuses on developing high-performance catalysts, such as those made from nickel or cobalt alloys, which reduce the energy required for water splitting. These catalysts facilitate the reaction at lower voltages, leading to significant energy savings. Optimizing electrode surface area and enhancing conductivity can further improve energy efficiency, making electrochemical hydrogen production more sustainable.Battery technology is another area where energy efficiency is critical. Lithium-ion batteries' energy losses during charging and discharging cycles significantly affect battery life and performance. Researchers are developing materials that exhibit lower resistance and improved ionic conductivity to address this. Advanced separator materials, such as ceramic-based separators, help reduce internal energy losses, leading to more efficient energy storage and extended battery life. Furthermore, solid-state batteries, which replace liquid electrolytes with solid materials, offer significant energy efficiency improvements by reducing the risk of energy losses through leakage or short-circuiting(Lai et al. 2022; Song et al. 2020).Supercapacitors, known for their rapid charge and discharge capabilities, also benefit from energy efficiency advancements. While supercapacitors typically store less energy than batteries, they can deliver it quickly, making them ideal for applications requiring high power output. Sustainable electrochemistry in supercapacitor design focuses on using materials with high surface area, such as graphene or carbon nanotubes, which maximize energy storage per unit volume and reduce the need for frequent recharging. By improving energy efficiency in supercapacitors, sustainable electrochemistry contributes to cleaner, more efficient energy systems supporting renewable energy integration.Another approach to improving energy efficiency is developing hybrid systems that combine electrochemical processes with renewable energy sources. For example, solar-powered electrochemical cells can harness sunlight to drive reactions, reducing the need for external electricity. In carbon capture and conversion, solar-driven electrochemical processes are being explored to convert CO_2 into valuable products with minimal energy input. This integration of renewable energy with electrochemical systems represents a significant advancement in sustainability, as it reduces dependence on fossil fuels and enhances the overall energy efficiency of the process.Energy efficiency also extends to designing and maintaining electrochemical cells used in industrial applications. Energy consumption can be minimized by reducing energy losses in cell design and improving system components, such as pumps and filters. Advanced monitoring and control systems can optimize real-time reaction conditions, ensuring energy is used effectively. These innovations contribute to a more sustainable industrial landscape, where electrochemical processes can operate with minimal environmental impact and lower energy requirements.Incorporating the principles of green chemistry into electrochemical processes is essential for advancing sustainable electrochemistry. Atom economy and waste reduction, using renewable resources and non-toxic solvents, and energy efficiency are critical components of this approach. Electrochemical systems reduce waste and material consumption by maximizing the atom economy and supporting a circular economy. Using renewable and non-toxic materials ensures that processes are safer for humans and the environment, while energy efficiency reduces the ecological footprint of electrochemical technologies. Through these principles, sustainable electrochemistry addresses immediate environmental concerns and paves the way for a more resource-efficient, low-impact future. As research and innovation continue to progress in this field, sustainable electrochemical applications have the potential to make significant contributions to global sustainability efforts across multiple sectors(Olabi et al. 2022; Abdel et al. 2021).

III. Electrochemical Water Treatment and Purification

Water pollution, scarcity, and contamination are among the most pressing environmental challenges of our time, directly impacting both human health and ecological systems. Innovative water treatment and purification approaches have become increasingly critical as demand for clean water continues to rise, particularly in rapidly urbanizing and industrializing areas. Traditional water treatment methods, though effective, often rely on chemicals and generate waste that can further harm the environment. Electrochemical water treatment offers a promising alternative, utilizing electricity to drive chemical reactions that degrade pollutants, remove heavy metals, and desalinate water with minimal environmental impact. This approach is sustainable and adaptable to various scales, from large municipal systems to smaller portable units for emergency use(Chowdhary et al. 2020; Schwarzenbach et al. 2010). This section explores three primary electrochemical water treatment techniques: advanced oxidation processes for wastewater treatment, electrochemical desalination and membrane technologies, and heavy metal removal and pollutant degradation.Advanced Oxidation Processes (AOPs) are chemical treatment procedures designed to remove organic contaminants from water by generating highly reactive species, such as hydroxyl radicals (·OH). These radicals react with various pollutants, breaking down complex organic molecules into simpler, non-toxic compounds, primarily water and carbon dioxide. Among the AOPs, electrochemical oxidation is an environmentally friendly and practical approach for degrading persistent contaminants in wastewater.Electrochemical oxidation utilizes electrodes to generate oxidizing agents in situ, reducing the need for external chemicals. For example, reactive oxygen species like hydroxyl radicals, ozone, and hydrogen peroxide are produced when an electric current is passed through water. These species have oxidizing solid properties, enabling them to break down contaminants such as pharmaceuticals, pesticides, and dyes that are typically resistant to conventional treatment methods(Cheng et al. 2016; Wang and Wang, 2020). This process is precious for treating industrial wastewater, which often contains high levels of toxic organic compounds.One notable advantage of electrochemical oxidation is its ability to target specific pollutants by adjusting reaction parameters, such as the electrode material and applied voltage. For instance, boron-doped diamond (BDD) electrodes have proven effective in generating hydroxyl radicals without producing harmful by-products, as they exhibit high stability and oxidation potential. As a result, BDD electrodes are widely used in electrochemical AOP systems for treating wastewater from industries like pharmaceuticals, textiles, and petrochemicals.Additionally, electrochemical AOPs can be integrated with other water treatment technologies to enhance their effectiveness. For example, combining electrochemical oxidation with photocatalysis—where light activates a catalyst—can improve the breakdown of organic contaminants. This hybrid approach allows for the simultaneous removal of a broader range of pollutants and can be particularly useful for treating wastewater with complex pollutant compositions. Electrochemical AOPs also offer a modular design, allowing them to be scaled and tailored for various applications, from extensive industrial facilities to decentralized systems in rural areas.Despite its advantages, the electrochemical AOP approach does have some limitations. Energy consumption can be a concern, especially when treating large volumes of wastewater or targeting highly resistant contaminants. However, ongoing research in electrode materials and process optimization is helping to improve the energy efficiency of electrochemical oxidation, making it a more viable option for widespread adoption(Ganiyu and Martínez- Huitle, 2019; Panizza et al. 2008).Desalination, the process of removing salts and other dissolved ions from water, has become increasingly important in addressing global water scarcity. Traditional desalination methods, such as reverse osmosis (RO) and distillation, are effective but energy-intensive, limiting their use in resource-constrained areas. Electrochemical desalination, an emerging approach, offers a potentially more energy-efficient and environmentally friendly solution by utilizing electrochemical reactions to separate ions from water.One of the primary electrochemical desalination methods is capacitive deionization (CDI). In CDI, water flows between two porous electrodes, which are charged to attract and adsorb dissolved ions. Positive ions (cations) move toward the negatively charged electrode, while negative ions (anions) move toward the positively charged electrode. This process effectively removes salts from the water, producing freshwater without the high energy demands associated with pressure-driven processes like reverse osmosis. CDI is particularly suited for treating low to moderately saline water and is less energy-intensive than traditional desalination methods, making it an ideal solution for brackish water sources.Advancements in electrode materials have significantly improved the performance of CDI systems(Qin et al. 2019; Maheshwari and Agrawal, 2020). For instance, electrodes made from activated carbon, graphene, and carbon nanotubes exhibit high surface areas and conductivity, allowing for more efficient ion adsorption and faster desalination rates. Additionally, modifications in electrode design, such as asymmetric CDI (where one electrode has a higher surface area than the other), have further enhanced the desalination efficiency of these systems.Another promising electrochemical desalination technique is electrodialysis (ED), which uses ion-selective membranes to separate ions from water. In an electrodialysis system, alternating cation- and anion-exchange membranes are placed between electrodes. When an electric field is applied, cations and anions are drawn through their respective membranes, leaving desalinated water in the central compartment. Electrodialysis is particularly effective for desalinating water with low to moderate salinity levels and is commonly used in applications like brackish water treatment and industrial wastewater desalination. The technology's modular design also allows for scalability, making it adaptable to various treatment capacities.A newer approach, reverse electrodialysis (RED), takes advantage of the salinity gradient between freshwater and seawater to generate electricity, which can then be used to desalinate water or power other electrochemical systems. In RED, ions flow through ion-selective membranes from high-salinity seawater to low-salinity freshwater, creating a voltage across the membranes. This method, still mainly in the experimental phase, represents a sustainable option for desalination, as it utilizes natural salinity gradients and reduces reliance on external energy sources.While electrochemical desalination methods are promising, they also face challenges(Sedighi et al. 2023; Koseoglu-Imer and Karagunduz, 2018). CDI, for example, is generally more effective for lower salinity levels and may require pre-treatment to remove organic contaminants that could foul the electrodes. Similarly, ion-selective membranes used in electrodialysis are susceptible to fouling and require periodic cleaning or replacement. Despite these challenges, ongoing advancements in materials science and process engineering continue to improve the efficiency and resilience of electrochemical desalination systems, making them an increasingly attractive option for sustainable water treatment.Heavy metals, such as lead, mercury, cadmium, and arsenic, are toxic pollutants that pose serious health risks and environmental hazards, even at low concentrations. Unlike organic contaminants, heavy metals do not degrade naturally and can accumulate in living organisms, causing long-term harm. Electrochemical methods offer a powerful approach for removing heavy metals from water by depositing them on electrodes or converting them into less harmful forms.Electrocoagulation is a widely used electrochemical technique for removing heavy metals and other pollutants from water. In electrocoagulation, a current is passed through sacrificial electrodes, typically iron or aluminum, which release metal ions into the water. These ions form hydroxides that bind to contaminants, creating flocs that can be easily separated from the water by sedimentation or filtration. Electrocoagulation effectively removesmany pollutants, including heavy metals, suspended solids, and organic matter, making it a versatile solution for treating industrial wastewater and contaminated groundwater.Another electrochemical method for heavy metal removal is electrodeposition, in which heavy metal ions are reduced and deposited as solid metal on an electrode. This approach is beneficial for recovering valuable metals, such as copper, silver, and gold, from wastewater streams. Electrodeposition removes toxic metals and allows for the recovery and recycling of metals, supporting the principles of a circular economy. Advances in electrode materials, such as using carbon-based materials with high surface areas, have improved the efficiency and selectivity of electrodeposition processes; for organic pollutants and persistent contaminants like pesticides and pharmaceutical residues, electrochemical oxidation and reductive dechlorination are commonly used techniques(Zhang et al. 2019; Lei et al. 2019). In electrochemical oxidation, reactive species generated at the electrode surface degrade complex organic molecules into non-toxic end products, such as water and carbon dioxide. This process is particularly effective for treating contaminants resistant to biological degradation. On the other hand, reductive dechlorination involves breaking down chlorinated organic compounds, such as polychlorinated biphenyls (PCBs) and trichloroethylene (TCE), by removing chlorine atoms through electrochemical reduction. This approach renders the pollutants less toxic and more amenable to further treatment or natural degradation.Combining electrochemical therapy with other techniques can enhance the removal of heavy metals and other pollutants. For example, integrating electrochemical processes with adsorption methods, such as using activated carbon or zeolites, can increase the removal efficiency and allow the capture of a broader range of contaminants. Similarly, coupling electrochemical treatment with biological processes, like microbial fuel cells, enables the simultaneous degradation of organic pollutants and removal of heavy metals, providing a comprehensive solution for treating complex wastewater(Shestakova and Sillanpää, 2017; Moradi et al. 2020).

IV. Conclusion

Sustainable electrochemistry has emerged as a transformative approach to tackling critical environmental issues, offering efficient, adaptable, and eco-friendly solutions across various applications. By applying green chemistry principles, sustainable electrochemical processes minimize waste, conserve resources, and reduce reliance on toxic chemicals, making them viable alternatives to conventional methods. Through innovations in advanced oxidation processes, electrochemical desalination, and heavy metal removal, these techniques enable effective water treatment and purification, addressing both water quality and scarcity issues in an environmentally responsible manner.Electrochemical methods also contribute significantly to carbon management, energy storage, and pollution monitoring, positioning them as essential tools for sustainability. Carbon capture and conversion, energy-efficient battery technologies, and electrochemical sensors offer solutions for reducing greenhouse gas emissions, enhancing renewable energy integration, and protecting natural ecosystems from pollutants. Each of these applications underscores the role of sustainable electrochemistry in creating a cleaner, more resilient future.However, challenges remain, including needing more energy-efficient processes, scalable technologies, and cost-effective materials. Ongoing research in electrode design, catalyst development, and hybrid systems will be crucial in overcoming these obstacles and maximizing the impact of sustainable electrochemical solutions on a global scale. Additionally, interdisciplinary collaboration and policy support will be vital to advancing these technologies from research to large-scale application.In summary, sustainable electrochemistry holds immense potential to address urgent environmental needs through innovative, low-impact technologies. As research progresses and these solutions are further developed, sustainable electrochemical applications will undoubtedly play a vital role in global sustainability efforts, helping to secure cleaner water, a stable climate, and healthier ecosystems for future generations.

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