

Perspective



# Electrochemical Technologies in Energy and Environment: Prospects, Developments, and Educational Perspectives

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**How To Cite:** Wang, Y.; Zheng, Z.; Huang, L.; et al. Electrochemical Technologies in Energy and Environment: Prospects, Developments, and Educational Perspectives. *Science for Energy and Environment* 2026, 3(1), 4. <https://doi.org/10.53941/see.2026.100004>

Received: 28 April 2026

Revised: 18 May 2026

Accepted: 20 May 2026

Published: 25 May 2026

**Abstract:** With the escalating severity of global environmental pollution, electrochemical technology has emerged as a pivotal tool in environmental governance due to its high efficiency, eco-friendliness, and precise controllability. Electrochemical technology demonstrates significant potential in wastewater treatment, carbon dioxide management, resource recovery, and environmental monitoring by leveraging unique reaction mechanisms, including advanced oxidation/reduction, selective separation, and carbon capture. However, its widespread adoption is hindered by limitations in material performance, high operational costs, and system complexity. To advance the sustainable development of electrochemical technologies, future efforts should focus on nanomaterial innovation, integration with green processes, and the application of intelligent systems for optimization and control.

**Keywords:** electrochemical catalysis; electrochemical separation; carbon capture and conversion; intelligent applications

## 1. Introduction

The escalating severity of global environmental pollution, including contaminated water bodies, degraded soil, and climate change driven by greenhouse gas emissions, necessitates the development of efficient and sustainable remediation technologies. Electrochemical technology has emerged as a pivotal tool in environmental governance, distinguished by its high efficiency, environmental friendliness, precise controllability, and potential for automation [1,2]. Conventional environmental treatment technologies suffer from inherent limitations. Chemical methods (e.g., coagulation, Fenton oxidation) rely on continuous chemical inputs and generate secondary sludge or spent catalysts [3]. Biological processes, though economical for biodegradable organics, typically require long hydraulic retention times, are vulnerable to toxic shocks, and demand large land areas [4]. Membrane separation achieves physical removal but simply transfers pollutants to a concentrate stream, while membrane fouling necessitates frequent cleaning and energy-intensive pressure driving. In contrast, electrochemical technology operates with electrons as the primary reactant, avoiding external chemical addition and secondary waste streams. Reactions proceed at ambient temperature and pressure, enabling both oxidative degradation of recalcitrant pollutants and reductive recovery of heavy metals within a single system [5]. Moreover, electrochemical systems respond instantaneously to fluctuating loads through simple current adjustment, making them compatible with automated, decentralized treatment trains. These characteristics do not render electrochemical technology



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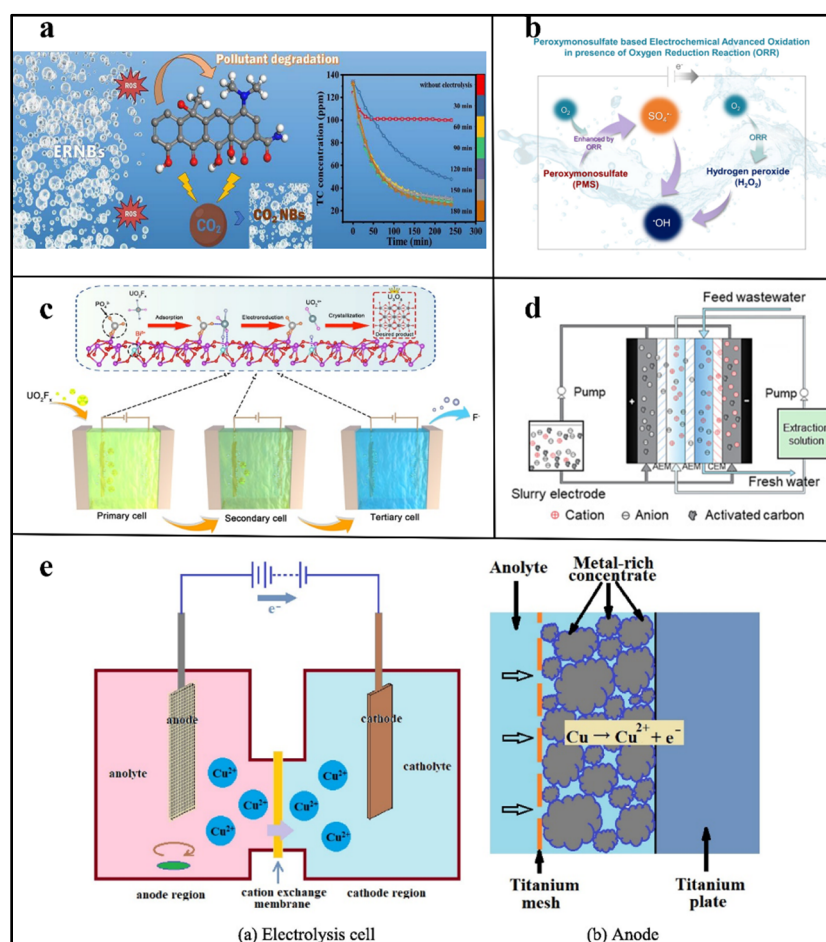
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universally superior; rather, they position it as a particularly attractive option for treating complex industrial effluents, recovering high-value resources, and integrating with renewable electricity. By utilizing electric fields to drive reactions at electrode surfaces, electrochemical technology can generate oxidizing agents, reductants, coagulants, or induce precipitation, enabling effective pollutant removal and resource recovery from various environmental matrices [6]. The applications of electrochemical technology in environmental protection are vast and can be strategically categorized into several core domains based on their primary mechanisms and objectives.

## 2. The Applications of Electrochemical Technology

### 2.1. Electrochemical Advanced Oxidation/Reduction Processes

These technologies are primarily employed for the degradation of persistent organic pollutants or the valency manipulation of heavy metals to reduce their toxicity and mobility. Yadav et al. [7] generated electrochemically reactive nanobubbles (ERNBs) via water splitting and utilized  $\text{CO}_2$  nanobubbles as a sustainable electrolyte alternative, achieving efficient degradation of tetracycline and simultaneous carbon utilization, as shown in Figure 1a. Lim et al. [8] revealed that the oxygen reduction reaction (ORR) critically enhances peroxymonosulfate (PMS)-based electrochemical advanced oxidation by generating  $\text{H}_2\text{O}_2$  and raising local pH, leading to a mixed sulfate/hydroxyl radical environment that significantly improves pollutant degradation, as shown in Figure 1b. Cui et al. [9] developed a scalable flow-through electrochemical oxidation device based on a membrane electrode assembly. Operating at 2 V, it achieved >92% removal of trace organic contaminants without generating secondary pollutants, and could be powered by solar energy.



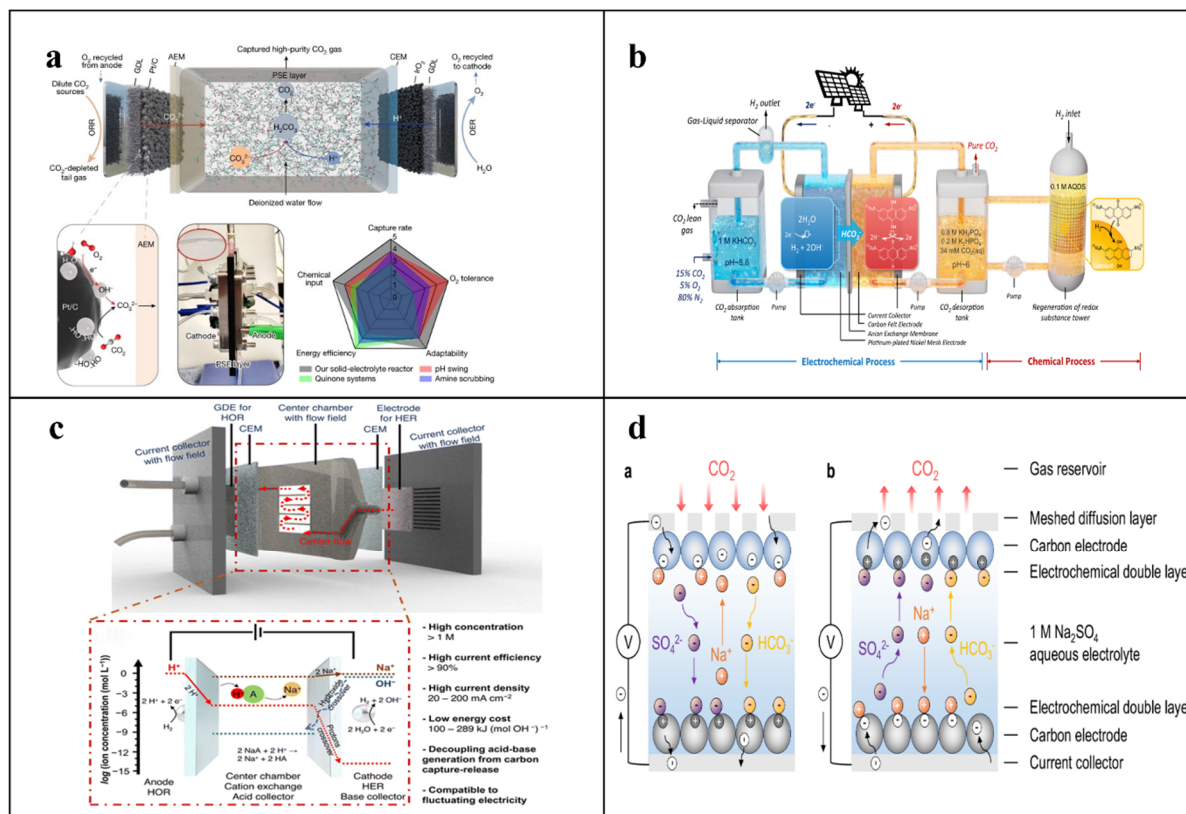
**Figure 1.** (a) Schematic of ERNBs-based AOP and TC degradation kinetics under different  $\text{CO}_2$  NB generation times. Reprinted with permission from Ref. [7]. Copyright © 2025, Elsevier Ltd. (b) Schematic of PMS-based EAOP enhanced by ORR, showing the synergistic generation of  $\text{SO}_4^{\cdot-}$  and  $\cdot\text{OH}$ . Reprinted from Ref. [8] under CC BY 4.0 license. Copyright © 2023, The Authors. (c) Schematic diagram of the uranium recovery device. Reprinted with permission from Ref. [10]. Copyright © 2025, Elsevier Ltd. (d) Schematic diagram of the improved FCDI system integrated with LMC. Reprinted with permission from Ref. [11]. Copyright © 2023, Elsevier B.V. (e) Schematic diagram of H-type electrolysis cell. Reprinted from Ref. [12] under CC BY 4.0 license. Copyright © 2024, The Authors.

## 2.2. Electrochemical Separation and Resource Recovery

This technology focuses on the selective separation and recovery of valuable resources from wastewater. Li et al. [10] constructed Lewis acid-base sites containing phosphate-deficient Bi ions ( $\text{PO}_4^{3-}\text{-Bi}^{\delta+}$ ) and integrated them into  $\text{Bi}_2\text{O}_3$  nanosheets to form  $\text{Ca}_5(\text{PO}_4)_3(\text{OH})\text{-Bi}_2\text{O}_{3-x}$  nanosheets. In addition, an electrochemical device was designed to avoid undesirable crystallographic transition of  $\text{K}_2\text{U}_2\text{O}_7$  by reasonably controlling the reaction period, achieving efficient recovery of high-purity uranium from nuclear wastewater, as shown in Figure 1c. Wu et al. [11] innovatively enhanced the flow electrode capacitive deionization (FCDI) technology by integrating a liquid membrane chamber (LMC) and an extraction solution composed of  $\text{Na}_2\text{SO}_3/\text{NaCl}$ . This system enabled the selective separation of chromium (Cr (VI)) and copper ions ( $\text{Cu}^{2+}$ ) in wastewater. Within the LMC, Cr (VI) was reduced *in situ* to Cr (III), facilitating its enrichment and recovery with a recovery rate exceeding 70%. Meanwhile, the activated carbon electrodes effectively adsorbed  $\text{Cu}^{2+}$ . Consequently, this process not only yielded freshwater but also produced high-purity chromium products and recyclable copper resources, as shown in Figure 1d. Li et al. [12] proposed a flotation-assisted electrodeposition process for recovering copper from discarded printed circuit boards. In order to improve the enrichment efficiency of copper, ethanol was used as the dispersion medium for flotation, and the efficient recovery of high-purity copper was achieved by optimizing the electrodeposition parameters, as shown in Figure 1e. Collectively, Figure 1a–e showcase how electrochemical reactions can be tuned for either oxidative degradation (a,b) or reductive/adsorptive recovery (c–e), all driven by electric-field-induced electron transfer at tailored interfaces.

## 2.3. Electrochemical Carbon Capture and Conversion

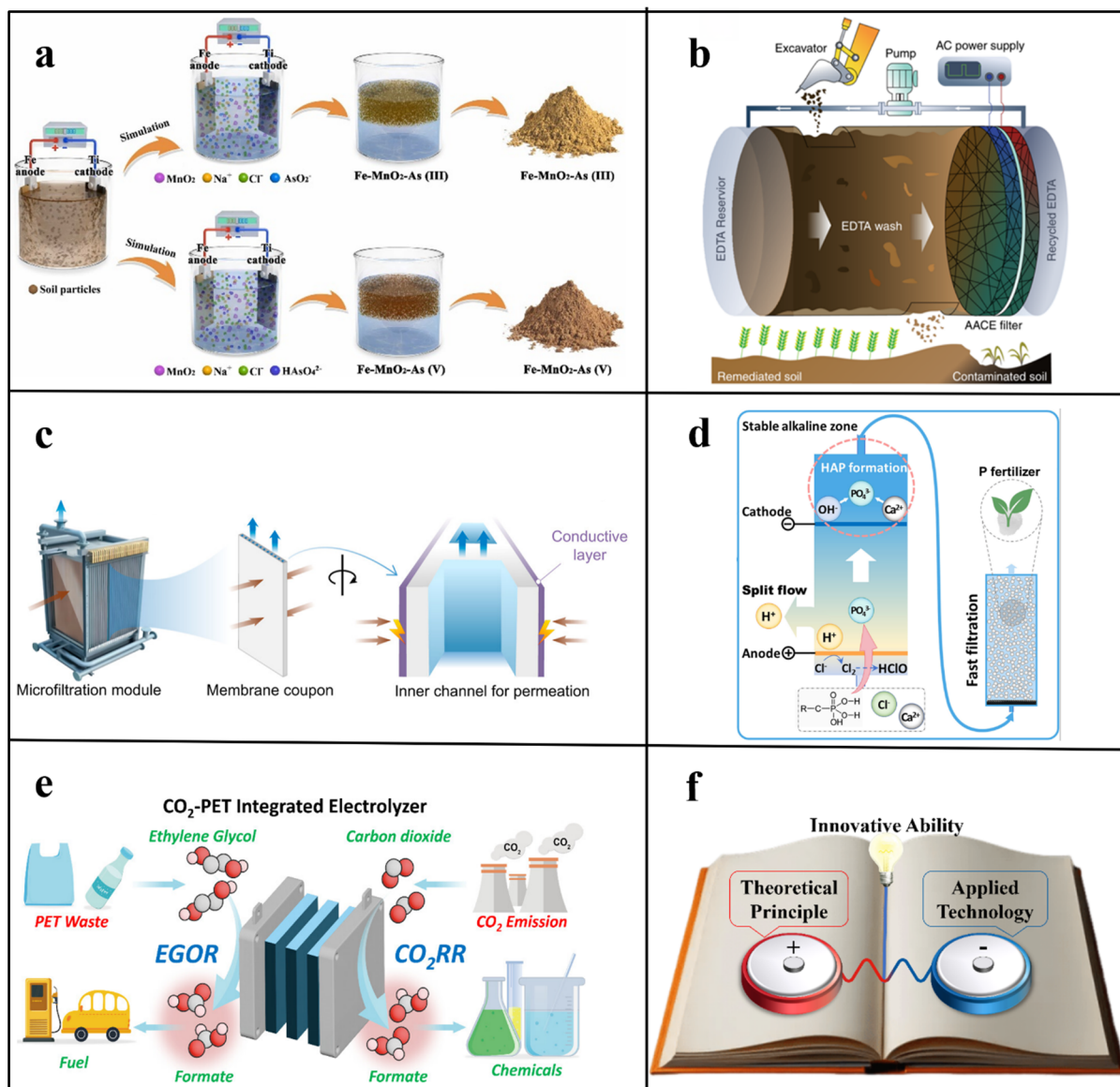
As a promising avenue for combating climate change, electrochemical technology offers innovative solutions for capturing and utilizing carbon dioxide. Zhu et al. [13] demonstrated a continuous electrochemical carbon capture technology and designed a solid electrolyte reactor that efficiently absorbed dilute  $\text{CO}_2$  molecules to form carbonate ions at the highly alkaline cathode membrane interface through oxidation-reduction electrolysis via oxygen reduction reaction (ORR) and hydrogen evolution reaction (OER). Through proton flux neutralization from the anode, high-purity (>99%)  $\text{CO}_2$  was continuously outputted, as shown in Figure 2a. Liu et al. [14] proposed an approach to decoupled redox electrochemical  $\text{CO}_2$  capture, which divided conventional single-step electrochemical reactions into two processes: electrochemical reactions and chemical redox reactions. In the electrolysis process, exploiting the hydrogen evolution reaction (HER) at the cathode and utilizing the anode for the oxidation of a redox carrier serves as a means to adjust the pH of the electrolyte. This adjustment was instrumental in achieving efficient  $\text{CO}_2$  capture, as shown in Figure 2b. Xi et al. [15] developed a three-room electrochemical system that efficiently generates high concentrations of acids (>1 M) and bases by decoupling carbon capture and electrochemical reactions, utilizing a serpentine channel design and weak acid buffer system. This system could effectively capture over 90% of  $\text{CO}_2$  in simulated flue gas and release high-purity  $\text{CO}_2$  through acid neutralization, as shown in Figure 2c. Xu et al. [16] systematically investigated the effects of electrode structure (high surface area, micro/mesopores, low oxygen functionalization) and charging protocols on supercapacitor-based electrochemical  $\text{CO}_2$  capture, achieving a capture rate of  $350 \text{ mmol CO}_2 \text{ kg}^{-1} \text{ h}^{-1}$ , low energy consumption of  $18 \text{ kJ mol}^{-1}$ , and excellent stability over 12,000 cycles, as shown in Figure 2d. Liu et al. [17] reported an electrified reversible surface mineralization strategy for direct air capture using  $\text{MnO}_2$ . Through Mn(III) redox cycling, the system achieved  $\text{CO}_2$  capture and release with an energy consumption of  $4.1 \text{ GJ/t CO}_2$  and stable operation over 1,000 h. Overall, Figure 2a–d illustrate four distinct electrochemical  $\text{CO}_2$  capture mechanisms—solid-electrolyte reactor (a), decoupled redox (b), acid-base generation (c), and supercapacitor-based adsorption (d)—highlighting the common strategy of decoupling the capture and release steps to improve energy efficiency.



**Figure 2.** (a) Solid-electrolyte reactor design for carbon capture from different CO<sub>2</sub> sources. Reprinted by permission from Springer Nature: Ref. [13], Copyright © 2023, The Author(s), under exclusive licence to Springer Nature Limited. (b) Schematic diagram of the decoupled redox electrochemical CO<sub>2</sub> capture system. Reprinted from Ref. [14] under CC BY 4.0 license. Copyright © 2024, The Authors. (c) Structure of the three-chamber two-membrane acid-base generator with components and flow labeled and schematic of the ion transport and concentration in the acid-base generator. Reprinted with permission from Ref. [15]. Copyright © 2025, American Chemical Society. (d) Schematic diagram illustration of supercapacitors for electrochemical CO<sub>2</sub> capture. Reprinted from Ref. [16] under CC BY 4.0 license. Copyright © 2024, The Authors.

## 2.4. Electrochemical Agricultural Application

Electrochemical technology is emerging as a promising tool for addressing agricultural challenges such as soil contamination, waterborne pathogens, and nutrient loss. Zhang et al. [18] used a pure iron plate as the anode and a titanium plate as the cathode to construct a two-electrode configuration electrochemical system. It was found that converting arsenic from an unstable to a stable state reduced the effective harm of arsenic in soil significantly by experiment. The removal mechanism of arsenic was analyzed through simulation experiments and cyclic voltammetry, as shown in Figure 3a. Xu et al. [19] developed a remediation method composed of a recirculating soil washing system and an electrochemical filtration device, which achieves high degrees of heavy metal removal from contaminated soil under a range of different concentrations, as shown in Figure 3b. Xiao et al. [20] fabricated a bipolar coplanar Janus membrane (BPCPM) using fractal Peano curve patterns, which enables efficient cogeneration of HClO and H<sub>2</sub>O<sub>2</sub> on the same membrane surface, achieving >5-log bacterial inactivation and enabling safe reuse of aquaculture wastewater for crop irrigation with low energy consumption (0.17 kWh m<sup>-3</sup>), as shown in Figure 3c. Xie et al. [21] developed a split-flow electrochemical oxidation coupled with filtration crystallization (SFE0-FC) system that converts >90% of EDTMP to orthophosphate within 20 min and achieves >90% phosphorus recovery as hydroxyapatite (HAP) in only 6 min, with the P-enriched Al<sub>2</sub>O<sub>3</sub> media being directly reusable as a slow-release fertilizer, as shown in Figure 3d. Yu et al. [22] designed an integrated electrolyzer coupling CO<sub>2</sub> reduction and ethylene glycol oxidation (derived from PET hydrolysis) using a 3D Ni foam anode and a Bi<sub>2</sub>O<sub>2</sub>CO<sub>3</sub>-based gas diffusion electrode, achieving ampere-level formate coproduction (1.2 A cm<sup>-2</sup>) with 65% energy saving and 100 h stability, as shown in Figure 3e. Together, Figure 3a–e demonstrate the versatility of electrochemistry in agriculture—from soil arsenic stabilization (a) and heavy metal removal (b) to pathogen inactivation (c), phosphorus recovery (d), and CO<sub>2</sub> upcycling (e)—while Figure 3f conceptually connects these applications back to electrochemical education.



**Figure 3.** (a) Schematic illustration about the different EC processes of Fe-Mn-As systems. Reprinted with permission from Ref. [18]. Copyright © 2024, Elsevier Ltd. (b) Schematic of an asymmetrical alternating current electrochemistry remediation system. Reprinted from Ref. [19] under CC BY 4.0 license. Copyright © 2019, The Authors. (c) Polarization design of a hollow, flat-sheet membrane. Reprinted with permission from Ref. [20]. Copyright © 2026, American Chemical Society. (d) Proposed split-flow electrochemical oxidation with filtration crystallization (SFEO-FC) system for P recovery. Reprinted with permission from Ref. [21]. Copyright © 2026, Elsevier Ltd. (e) Schematic diagram of the CO<sub>2</sub>-PET integrated electrolyzer. Reprinted from Ref. [22] under CC BY 4.0 license. Copyright © 2025, The Authors. (f) Schematic illustration of electrochemical knowledge transfer bridging fundamental principles and innovative applications in education.

### 2.5. Electrochemical Education

Despite the considerable promise of electrochemical technologies in environmental remediation, their practical deployment remains constrained by several persistent challenges, including insufficient long-term material stability, high energy consumption and operational costs, and inherent procedural complexity. Addressing these barriers depends critically on the advancement of electrochemical education. A strengthened educational foundation can cultivate a robust pipeline of skilled professionals equipped to drive technological innovation and translate laboratory advances into field-ready solutions. Within current environmental engineering curricula, however, electrochemistry is often relegated to an elective topic and lacks systematic course design. Conventional instruction tends to emphasize theoretical formalisms—such as the Nernst equation and electrode kinetics—while offering limited engagement with real-world application scenarios. Laboratory training similarly remains anchored in routine techniques (e.g., pH measurement and cyclic voltammetry) and seldom incorporates exposure to emerging characterization tools, including *in situ* methodologies and scanning electrochemical microscopy. Consequently,

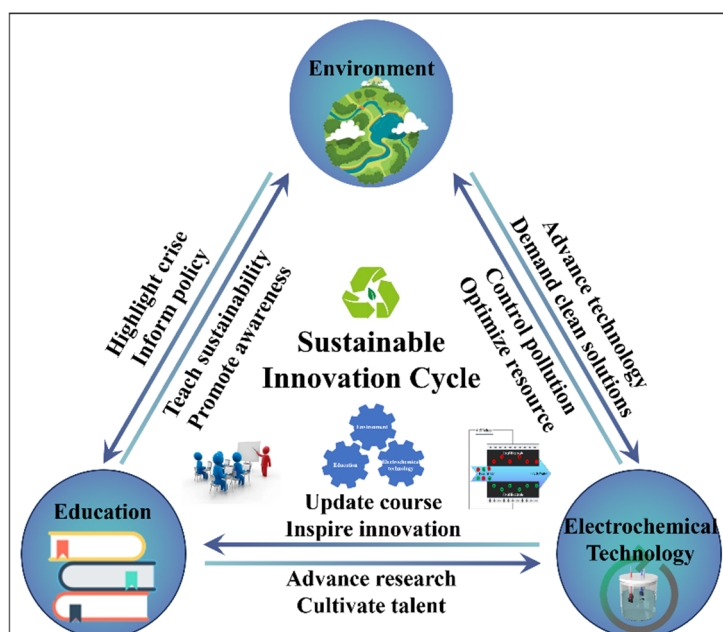
electrochemical education in higher education must evolve to integrate frontier research insights directly into the classroom and laboratory, thereby narrowing the gap between academic training and technological practice. As illustrated conceptually in Figure 3f, where an open book configured as an electrolytic circuit connects theoretical principles with applied technology, closing this gap demands curricular reform that responds to the rapid infusion of artificial intelligence into the field. For example, a problem-based learning module on electrochemical degradation of organic pollutants can be introduced, together with a simple assessment framework including lab reports, group project evaluation, and peer feedback. Such concrete pedagogical cases and assessment methods, though concise, demonstrate how educational perspectives can be embedded without overhauling the existing structure. Such reform is essential to prepare graduates who not only possess up-to-date knowledge of cutting-edge developments but also demonstrate the advanced problem-solving capacity required to tackle multifaceted environmental issues, ultimately underpinning the continued advancement and broader implementation of electrochemical strategies in environmental protection.

Despite this considerable promise, the widespread adoption of electrochemical technology faces significant challenges that hinder its full-scale implementation. These include limitations in electrode material stability and activity, high energy consumption and operational costs, system complexity in scaling up, and a lack of deep integration with other green processes. Furthermore, the effective design and optimization of these systems requires a cross-disciplinary approach that combines materials science, process engineering, and data analytics.

It is precisely these challenges that define the prospects of the field. We will explore the future development of electrochemical technology for environmental applications by focusing on three interconnected core pillars that are critical for overcoming current limitations: (1) Material innovation for enhanced efficiency and durability; (2) Green process integration for improved sustainability and resource circularity; (3) Intelligent application of artificial intelligence and data science for precise control and optimization. The following will explore in depth from the perspectives of material innovation, green process integration, and intelligent applications.

### 3. Future Prospect

Despite the significant progress in electrochemical environmental technology, its maturation and widespread deployment hinge on strategic advancements across three interdependent pillars: material innovation, green process integration, and intelligent application. These three directions are conceptually illustrated in Figure 4, which highlights their interconnected roles in promoting the sustainable development of electrochemical environmental technologies. The following sections delve into these core directions, outlining the pathways to overcome existing limitations and unlock the full potential of this field.



**Figure 4.** Conceptual diagram illustrating the three interconnected pillars for the sustainable advancement of electrochemical environmental technologies: Material innovation, Green process Integration, and Intelligent application.

### 3.1. Material Innovation

Electrode materials are the cornerstone of electrochemical systems, whose performance directly dictates reaction efficiency, selectivity, cost, and longevity. Traditional materials often suffer from limited active sites, poor stability, or high overpotentials.

In response to this challenge, the core direction of material innovation focuses on nanomaterials, novel compound materials, and composite materials. The electrochemical performance of nanomaterials can be significantly enhanced by controlling their size, shape, and structure. Nanostructured electrode materials can increase reactive sites and shorten ion diffusion pathways [23]. On the other hand, the exploration of novel compound materials should continue to advance, such as conductive organic frameworks, sulfides, single atoms, boron graphene, etc., with special properties, which may bring new application scenarios and development opportunities for electrochemical technology. In addition, the design and preparation of composite materials will also become a hot topic, combining the advantages of different materials, such as combining carbon materials with good conductivity and active substances, can synergistically improve electrochemical performance.

Beyond structural tuning, the exploration of novel compounds—such as single-atom catalysts, metal-organic frameworks (MOFs), and advanced metal sulfides/oxides—holds promise for achieving unprecedented activity and selectivity. Furthermore, composite materials that synergistically combine conductive substrates (carbon nanotubes, MXenes, laser-induced graphene) with highly active phases can overcome the limitations of individual components. For example, the integration of conductive polymers with 2D materials has been shown to enhance charge transfer and stability in heavy metal sensing and recovery [24]. The future lies in rational design, guided by fundamental mechanistic understanding and computational prediction, to develop next-generation electrodes with bespoke functionalities for complex environmental matrices.

### 3.2. Green Process Integration

Electrochemical technology is not only determined by its efficacy in pollutant removal but also by its overall energy consumption and resource utilization. The future direction emphatically shifts towards integrating electrochemical technology into a broader framework of green chemistry and the circular economy.

A paramount strategy is the direct coupling of electrochemical systems with renewable energy sources (e.g., solar, wind). This alignment not only decarbonizes the treatment process but also leverages the intermittent nature of renewables for flexible, cost-effective operation. The work of Xi et al. [15] was a quintessential example, where an electrochemical acid-base generator, potentially powered by renewables, facilitates carbon capture and concurrently produces chemicals for green cement production, effectively closing the loop.

Electrochemical processes can be designed to valorize pollutants, transforming waste streams into valuable products. This includes the electrochemical reduction of CO<sub>2</sub> to fuels or chemicals, the recovery of high-purity metals from industrial effluents, and the synthesis of chemicals from nitrogen or other abundant molecules. Replacing traditional, energy-intensive thermochemical processes with electrochemical alternatives represents a paradigm shift towards inherently safer and more sustainable industrial operations. The challenge lies in designing integrated systems that are energetically efficient, economically viable, and scalable.

### 3.3. Intelligent Application

Intelligent technologies are expected to enhance the efficiency and precision of electrochemical applications. In material design, machine learning and big data analytics can facilitate the rapid screening and performance prediction of new electrochemical materials, accelerating the process of material discovery and optimization. In the control and monitoring of electrochemical reactions, key parameters such as current, voltage, temperature, gas flow rate, etc., are obtained in real time through intelligent sensors and automated control systems, and reaction conditions are automatically adjusted based on these data to achieve precise control and optimization of electrochemical reactions and improve reaction rates [25,26]. At the same time, artificial intelligence algorithms are used to analyze and mine the operational data of electrochemical devices and systems, predict equipment failures in advance, optimize equipment maintenance and management strategies, reduce equipment operating costs and failure rates, and improve the reliability and stability of the entire electrochemical system.

Recent studies provide concrete examples beyond these general descriptions. For catalyst screening, combining DFT calculations with ensemble machine learning (Random Forest, Gradient Boosting, XGBoost) screened over 8000 heteroatom-doped carbon configurations for CO<sub>2</sub> electroreduction, achieving cross-validated R<sup>2</sup> of 0.8760 ± 0.0274 in predicting C<sub>2</sub><sup>+</sup> Faradaic efficiency [27]. For process optimization, a random forest model coupled with NSGA-II multi-objective optimization was applied to an electrooxidation-electrocoagulation system, achieving 87.71% ammonia and 94.51% phosphate removal from real aquaculture wastewater at an estimated cost of ~0.8 USD m<sup>-3</sup> [28]. For edge deployment, a neural network-assisted CNT electrochemical sensor array was integrated with solar-powered autonomous buoys, achieving 93.6% accuracy in classifying water pollutants into risk categories with only 1.2 ms latency and 1.8 MB memory usage [29]. Despite these advances, barriers remain—data heterogeneity across laboratories limits model transferability, and few digital twin implementations have been validated with long-term field data. Pan et al. [30] integrated a knowledge graph with seven large language models to construct a multi-agent artificial intelligence system (ECOMATS) for autonomous catalyst design. This system successfully discovered a novel peroxymonosulfate activation catalyst that degraded 90.5% of perfluorooctanoic acid within five minutes, significantly accelerating the screening process for water purification materials. The work exemplifies how multi-agent AI can bridge intelligent algorithm design with material innovation.

The three pillars are not independent. Machine learning, for example, can accelerate the identification of stable, low-cost electrode materials—linking material innovation with intelligent control. Digital twins, in turn, help match electrochemical reactor operation to variable renewable power, bridging green integration and intelligent application. Biodegradable or self-healing electrode designs reduce end-of-life environmental burden, aligning materials with green chemistry. Yet tensions also exist. High-performance nanomaterials often demand energy-intensive synthesis, which may offset their sustainability gains. Likewise, deploying real-time sensors and edge controllers adds hardware and energy overhead, an added cost that must be outweighed by operational efficiency improvements. Acknowledging both synergies and trade-offs is necessary if future work is to avoid treating the three pillars as separate agendas.

#### 4. Conclusions

Electrochemical technology stands at the forefront of innovative solutions for addressing pressing environmental challenges. Its ability to efficiently degrade pollutants, recover valuable resources, capture carbon, and enable real-time monitoring underscores its versatility and potential. However, to fully realize this potential, continued advancements in material science, process integration, and intelligent management are essential. The synergy between nanomaterials design, renewable energy coupling, and AI-driven optimization will pave the way for more sustainable, efficient, and scalable electrochemical systems. Future research should emphasize interdisciplinary collaboration to overcome existing barriers and accelerate the translation of laboratory successes into real-world applications, ultimately contributing to a cleaner and more sustainable planet.

#### Author Contributions

Y.W.: Writing, drawing pictures. Z.Z.: Drawing pictures. L.H.: Guidance, Revision. J.Y.: Revision. Z.C.: Revision. M.L.: Revision. H.Z.: Guidance, Revision. All authors have read and agreed to the published version of the manuscript.

#### Funding

This work was supported by the National Natural Science Foundation of China (52470079), the 2025 Guangdong Provincial Undergraduate Higher Education Teaching Quality and Teaching Reform Project, Guangzhou University 2026 Experimental Teaching Reform Research Project, and the Provincial Natural Science Foundation of Guangdong (2024A1515012707).

#### Data Availability Statement

Data will be made available on request.

#### Conflicts of Interest

The authors declare no conflict of interest.

## Use of AI and AI-Assisted Technologies

During the preparation of this work, the author used DeepSeek to translate and revise. After using this tool, the author reviewed and edited the content as needed and take full responsibility for the content of the published article.

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