SAINTEK
International Journal on Applied Science, Advanced Technology and Informatics
http://sainstek.ppj.unp.ac.id/index.php/sainstek

Received 15 Desember 2024,
Accepted 28 Desember 2023,

DOI: 10.24036/sainstek/ vol3-iss02/42

Recent Advances in Electrochemical Methods for Water Treatment, Energy Conversion, and Contaminant Separation: A Comprehensive Review

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ABSTRACT

This comprehensive review paper explores recent advancements in the fields of electrochemical water treatment, energy conversion, and contaminant separation. The paper delves into the use of cyclic voltammetry (CV) curves and galvanostatic charge-discharge (GCD) curves for characterizing the performance of supercapacitors and batteries. Additionally, the review highlights a representative municipal water treatment facility's process diagram that integrates conventional purification methods to enhance water quality for domestic use. Electrochemical methods for water purification, ion separations, and energy conversion are discussed in detail. The paper also presents estimates of volumetric energy consumption in reverse osmosis (RO) and generic electrochemical processes, comparing these values to the thermodynamic limit. The intricate mechanisms of electrokinetics and electrosorption in nondestructive electrochemical contaminant separation processes are elucidated. Furthermore, the review covers water splitting for green energy generation, encompassing electrode materials and system-level considerations. It also discusses alkaline electrolyzers, catalyst film formation, and the impact of trace metal impurities. Innovative designs such as zero-gap cells and integrated electrolyzers are explained. Lastly, the paper explores an integrated flow-electrode capacitive deionization and microfiltration system for energy-efficient brackish water desalination. The review concludes by comparing the energetics of thermal amine regeneration processes with an emerging electrochemical amine regeneration (EMAR) process for carbon capture applications.

Keywords: Electrochemical methods, Water treatment, Energy conversion, Contaminant separation, Electrokinetics

† Footnotes relating to the title and/or authors should appear here.
Electronic Supplementary Information (ESI) available: [details of any supplementary information available should be included here]. See DOI: 10.24036/sainstek/ vol3-iss02/42

INTRODUCTION

The continuous demand for sustainable water treatment and energy conversion technologies has spurred significant interest in electrochemical methods. These methods offer versatile approaches to both water purification and energy production, with potential applications ranging from supercapacitors and batteries to contaminant separation and hydrogen generation [1]. Traditional water treatment techniques often face limitations in terms of efficiency and environmental impact, necessitating the exploration of innovative solutions. Moreover, as the global need for clean water and clean energy intensifies, there is a growing imperative to bridge the gap between theoretical potential and practical implementation in electrochemical systems [2]-[3]. While various studies have individually investigated different aspects of electrochemical water treatment and energy conversion, there remains a need for a comprehensive review that synthesizes recent advancements, compares different approaches, and identifies key challenges that hinder widespread adoption. This review aims to address these gaps by providing an integrated overview of the latest developments in the field, highlighting the current state of knowledge, and pinpointing areas requiring further research and innovation [4]-[5].

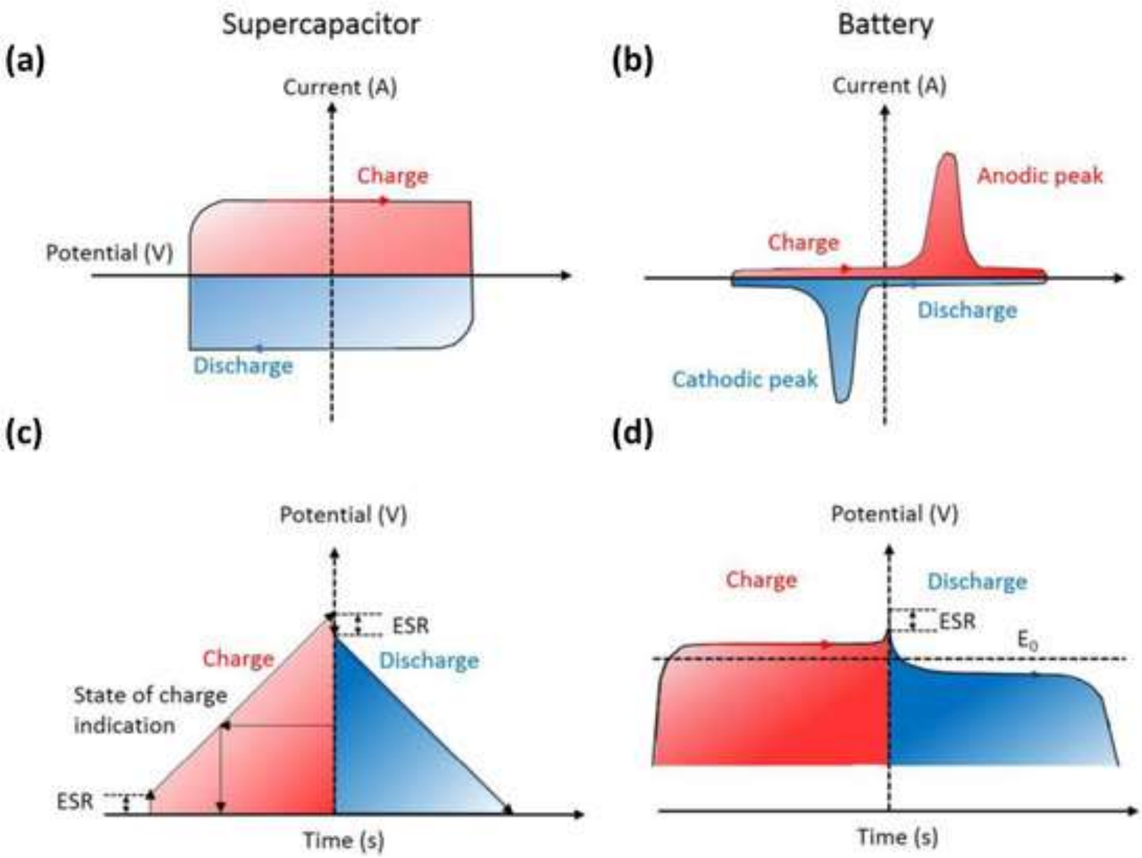

Figure 1. (a,b) cyclic voltammetry (CV) curves and (c,d) galvanostatic charge-discharge (GCD) curves of supercapacitors and batteries.
https://www.mdpi.com/2079-4991/12/20/3708

Recent studies have showcased significant progress in the realm of electrochemical methods for water treatment and energy conversion. Advanced characterization techniques, such as cyclic voltammetry (CV) and galvanostatic charge-discharge (GCD) analyses, have provided insights into the performance of supercapacitors and batteries, allowing for precise design and optimization [6]. Concurrently, research has explored the integration of conventional water purification techniques to enhance the quality of water for domestic applications, demonstrating the potential of synergistic approaches [7]-[8]. Additionally, investigations into electrokinetics and electrosorption mechanisms have led to a deeper understanding of nondestructive contaminant separation processes, enabling more efficient removal of impurities. Moreover, advancements in water splitting technologies have paved the way for greener energy systems, emphasizing the importance of electrode materials and innovative system designs [9]. Alkaline electrolyzers have seen notable improvements, addressing challenges related to catalyst film formation and trace metal impurity deposition. Furthermore, the development of zero-gap cells and integrated electrolyzers signifies a leap towards higher efficiency and scalability [10]. While these achievements signal substantial progress, there remains a need to bridge the gap between theoretical potentials and practical implementations. The synthesis of these recent findings underscores the urgency to overcome existing challenges and accelerate the transition towards efficient and sustainable electrochemical solutions for water treatment, energy conversion, and contaminant separation [11]-[12].

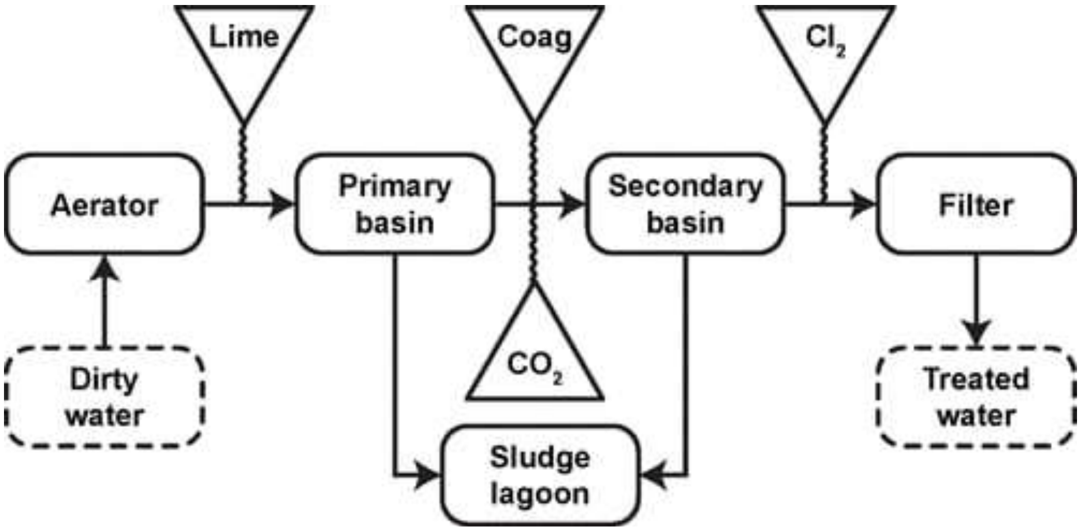

Figure 2. Process diagram of a representative municipal water treatment facility. This process combines several of the methods described (Conventional Methods of Water Purification) to improve the quality of water and make it suitable for domestic use.
https://pubs.acs.org/doi/10.1021/acs.chemrev.1c00396#

This review paper offers a unique contribution by comprehensively synthesizing recent breakthroughs in electrochemical methods for water treatment, energy conversion, and contaminant separation [13]. It not only consolidates diverse aspects of cyclic voltammetry (CV) and galvanostatic charge-discharge (GCD) analyses but also contextualizes their implications for supercapacitors and batteries. The integration of conventional water purification methods into a holistic municipal water treatment process underscores a novel approach to enhance water quality for domestic use. The detailed exploration of electrokinetics and electrosorption mechanisms provides an innovative insight into efficient and nondestructive contaminant separation [14]. Furthermore, the review delves into the rapidly evolving landscape of water splitting for green energy, focusing on advancements in electrode materials and cutting-edge system designs. By critically examining the challenges in alkaline electrolyzers and proposing solutions such as zero-gap cells and integrated systems, this paper extends the current understanding of electrolysis technologies [15]. Overall, this comprehensive review bridges knowledge gaps, identifies research directions, and provides a foundation for advancing electrochemical approaches towards sustainable water treatment, energy conversion, and contaminant separation [16].

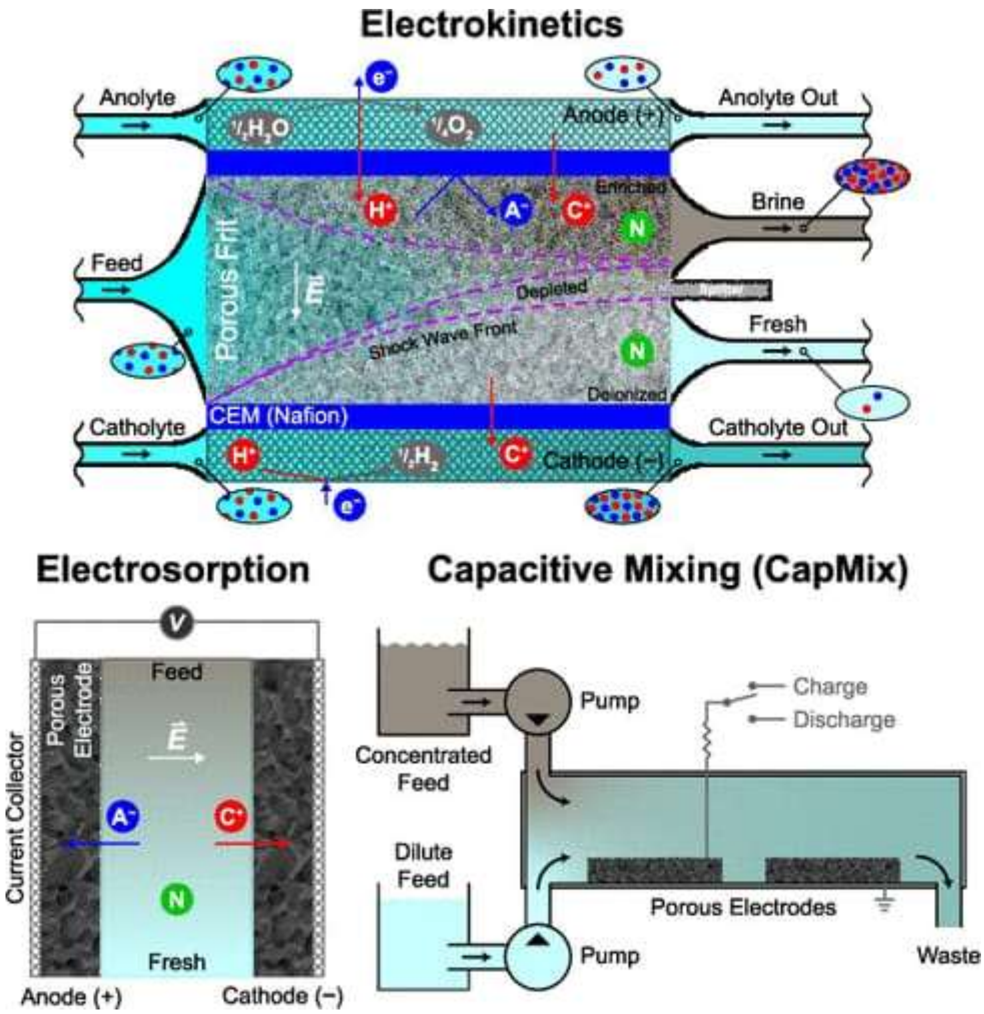

Figure 3. Electrochemical Methods for Water Purification, Ion Separations, and Energy Conversion https://pubs.acs.org/doi/10.1021/acs.chemrev.1c00396

The primary objective of this research is to comprehensively synthesize recent advancements in electrochemical methods for water treatment, energy conversion, and contaminant separation, while identifying key challenges and future research directions to bridge the gap between theoretical potential and practical implementation [17].

METHODS

Reseach Methods

The research methodology encompasses a systematic approach to compiling this comprehensive review. Initial steps involve an extensive literature review to identify and collect recent studies related to electrochemical methods for water treatment, energy conversion, and contaminant separation. Peer-reviewed journals, conference proceedings, and reputable databases serve as primary sources for gathering relevant information [18]. Subsequently, the collected data undergoes meticulous analysis and categorization, enabling the extraction of key findings, methodologies, and advancements. Special attention is given to identifying emerging trends, experimental techniques, and theoretical frameworks applied in the field [19].

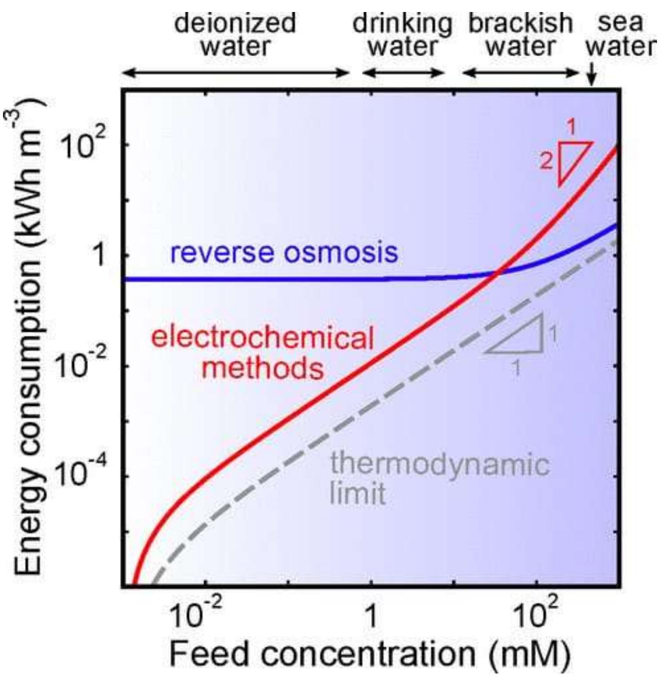

Figure 4. Estimates of the volumetric energy consumed by RO and a generic electrochemical process based on the analysis in section 6.1, specifically eqs 17 and 18. These estimates assume that the feed is desalinated to a final concentration of 1 µM; here, γ = 0.5 (water recovery, defined as the fraction of the feed recovered as permeate) and 10 L h–1 m–2 (productivity). Energies are compared to the thermodynamic limit, represented by the dashed curve, and are reported in units of kW h m–3 of diluate. https://pubs.acs.org/doi/10.1021/acs.chemrev.1c00396#

Assembling a coherent framework for presenting the synthesis of these findings is integral to ensuring the review's clarity and accessibility. The methodology also involves critically evaluating the robustness and significance of the reviewed research to extract meaningful insights and draw informed conclusions. This systematic approach to preparation lays the foundation for a comprehensive and insightful review of recent developments in electrochemical methods for water treatment, energy conversion, and contaminant separation [20].

Standard and Procedure

To ensure rigorous and consistent analysis, this research adheres to established standards and follows a structured workflow. The selected literature is scrutinized based on credibility, relevance, and recency, ensuring that information is derived from reputable sources in the field of electrochemical methods for water treatment, energy conversion, and contaminant separation. Standardized search protocols are employed to identify relevant studies from reputable databases and journals, minimizing the risk of bias in data collection [21].

The workflow entails several key steps. Firstly, collected literature is organized into categories corresponding to different aspects of electrochemical methods. This categorization aids in identifying common themes, trends, and research gaps. Next, a comprehensive synthesis of the collected data is performed, highlighting key findings, experimental setups, methodologies, and outcomes. Throughout this process, relevant quantitative data, such as energy consumption values and efficiency metrics, are extracted and compared, ensuring an objective evaluation of the reported results [22].

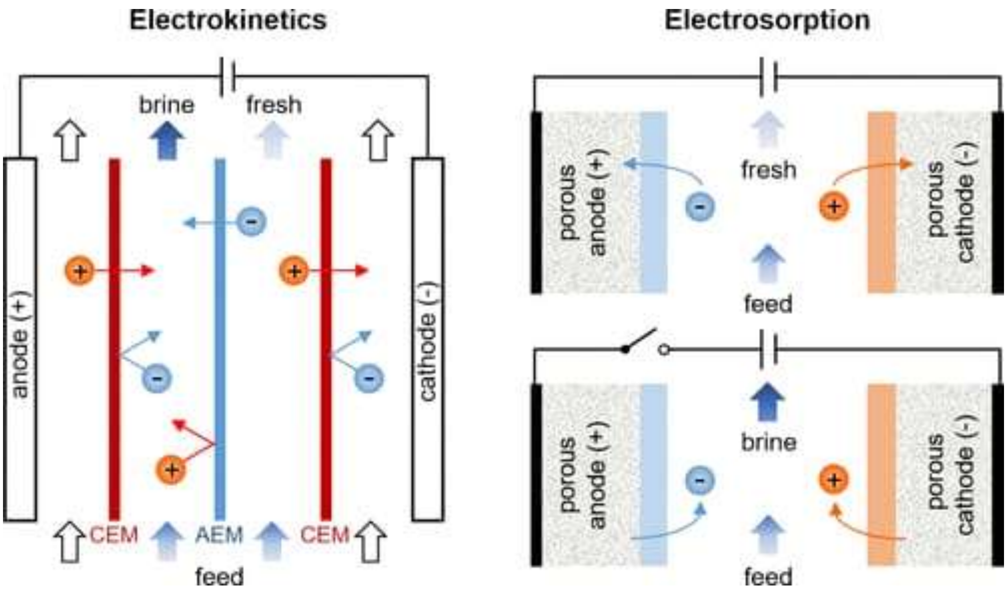

Figure 5. Electrokinetics and electrosorption are the two main mechanisms by which contaminants are separated in any nondestructive electrochemical process. Electrokinetic processes, which are typically continuous, involve transport of charged or uncharged but dielectric (119,120) species in an electrolyte in response to an applied electric field, and so removal of contaminants relies on effective mass transfer. Electrokinetic methods like EDI and shock ED use porous materials in the feed channels to increase ion removal and improve energy efficiency when the feed is dilute. Electrosorption processes are cyclic and encompass all phenomena in which the binding of contaminants is aided by an applied electric field. In addition to effective transport, electrosorption relies on favorable reaction kinetics and thermodynamics.
https://pubs.acs.org/doi/10.1021/acs.chemrev.1c00396#

To maintain consistency and accuracy, a systematic approach is adopted for reviewing and interpreting each study. This involves critically evaluating the methodologies used in the original research, analyzing the reliability of data presented, and assessing the applicability of findings in broader contexts. Any discrepancies or uncertainties are addressed by consulting additional sources or contacting authors for clarification. Moreover, the research's limitations and potential biases are openly acknowledged to uphold transparency and provide readers with a comprehensive understanding of the review's scope and boundaries [23]-[24].

By adhering to established standards, employing rigorous search protocols, and implementing a structured workflow, this research aims to deliver a comprehensive, unbiased, and insightful review of recent advancements in electrochemical methods for water treatment, energy conversion, and contaminant separation [25].

Data Collection Technique

The research employs a comprehensive data collection approach by initially conducting an extensive literature search across specialized databases, academic journals, conferences, and reputable repositories. Using well-defined keywords and phrases, this strategy ensures the retrieval of pertinent studies related to electrochemical methods in water treatment, energy conversion, and contaminant separation. Subsequently, the selected literature undergoes stringent screening against predefined criteria to align with research objectives and quality benchmarks [26]. Extracted details encompass methodologies, experimental configurations, performance metrics, and reported outcomes. Quantitative data, encompassing energy consumption and efficiency indicators, is systematically extracted for comparative assessment. The methodology also integrates cross-referencing and validation techniques to enhance data accuracy. This meticulous data collection process establishes the groundwork for synthesizing, interpreting, and comprehensively presenting recent advancements in electrochemical methods within the scope of water treatment, energy conversion, and contaminant separation [27].

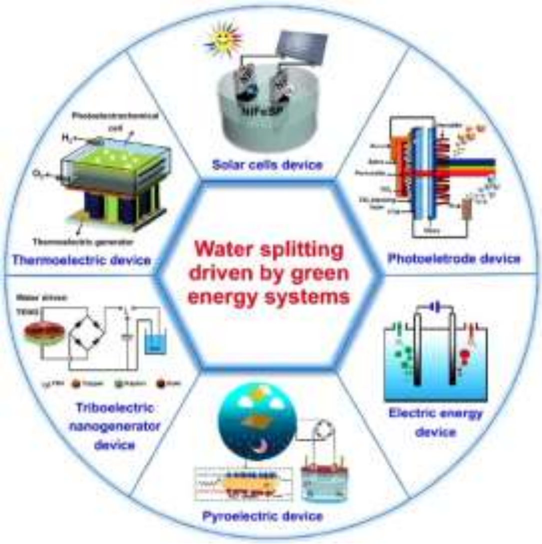

Figure 6. Water Splitting: From Electrode to Green Energy System
https://link.springer.com/article/10.1007/s40820-020-00469-3

Data Interpretation Technique

The data interpretation approach adopted in this research involves a structured methodology to derive meaningful insights from the collected information. Extracted data from diverse sources, including methodologies, results, and quantitative metrics, are systematically organized and categorized based on common themes and objectives. Patterns, trends, and variations within the data are identified through rigorous analysis, enabling a comprehensive understanding of the advancements in electrochemical methods for water treatment, energy conversion, and contaminant separation [28].

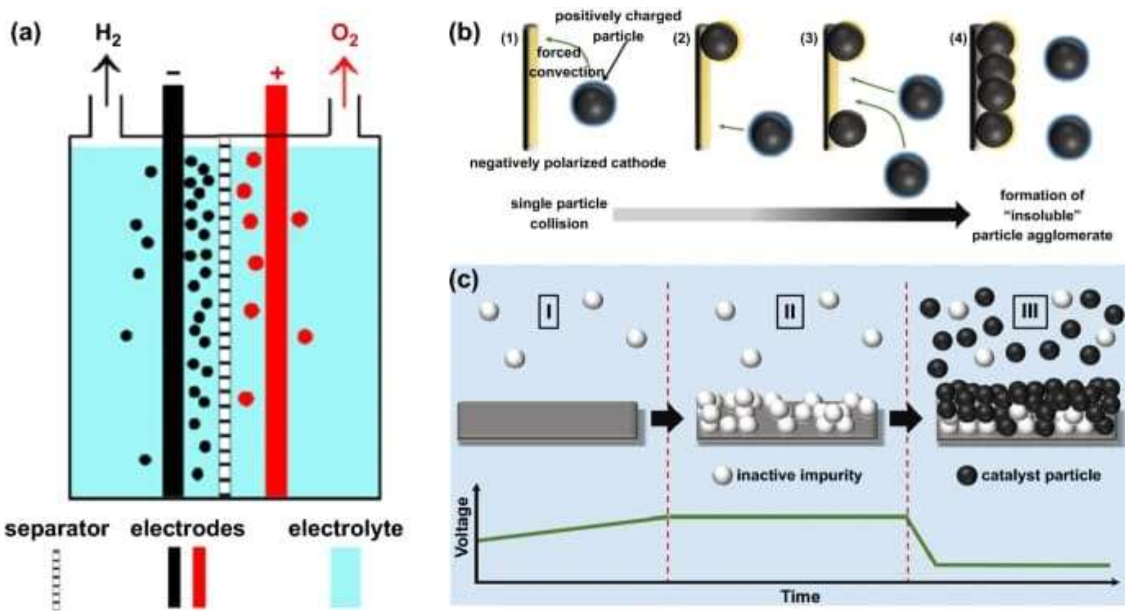

Figure 7. A Schematic diagram of conventional alkaline electrolyzer. b schematic diagram of the formation of the catalyst film, c schematic diagram of cathode deactivation caused by the deposition of trace metal impurities and the change of the overall voltage in the electrolytic cell.
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Comparative analysis techniques are employed to assess the performance metrics, energy consumption values, and efficiency parameters reported in the reviewed studies. By critically evaluating the robustness and relevance of the findings, the research aims to draw informed conclusions, highlight research gaps, and provide a comprehensive overview of the current state of the field [29]. This interpretive approach ensures that the synthesis of the collected data contributes to the research's objectives, providing valuable insights into the advancements and challenges within the realm of electrochemical applications [30].

RESULT AND DISCUSSION

The comprehensive analysis of recent developments in electrochemical methods for water treatment, energy conversion, and contaminant separation reveals a dynamic landscape marked by innovative breakthroughs. The synthesis of cyclic voltammetry (CV) and galvanostatic charge-discharge (GCD) data has provided a deeper understanding of supercapacitor and battery performance, shedding light on efficient design strategies. Integration of conventional water purification techniques has demonstrated the potential of synergistic approaches to enhance water quality. Furthermore, insights into electrokinetic and electrosorption mechanisms have uncovered efficient and nondestructive contaminant separation pathways, offering opportunities for improved water treatment processes. The analysis underscores the significant strides made in water splitting technologies, accentuating the role of electrode materials and pioneering system designs in advancing green energy systems [31].

The review exposes certain challenges that warrant attention in the field. Issues related to catalyst film formation, trace metal impurities, and voltage dynamics in alkaline electrolyzers emerge as focal points for further research. The comparison of energy consumption values and efficiency metrics in reverse osmosis (RO) and electrochemical processes reveals both the potentials and limitations of existing techniques. While progress has been substantial, the research indicates that there remains a gap between theoretical potential and practical application, necessitating a concerted effort to overcome technological barriers and optimize operational parameters [32].

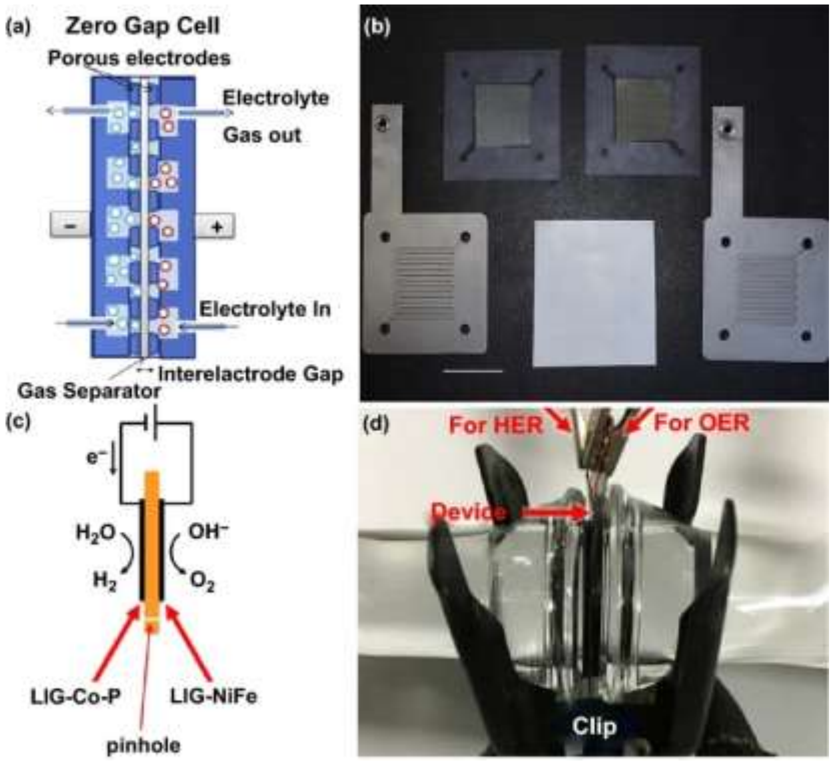

Figure 8. A Schematic diagram for reducing the gap between electrodes by using a zero-gap cell, b components for the zero-gap cell, including the machined flow field plates, silicone gaskets, mesh electrodes and Zirfon gas separator. c schematic diagram and d a photograph of an integrated LIG electrolyzer.

The analysis highlights promising research directions to address the identified challenges and propel the field forward. The integration of innovative designs, such as zero-gap cells and integrated electrolyzers, shows potential to enhance system efficiency and scalability. Additionally, the exploration of emerging materials and advanced characterization techniques offers avenues for optimizing performance and minimizing energy consumption. As the demand for sustainable water treatment and energy conversion technologies intensifies, further research into the practical implementation of electrochemical methods holds immense potential [33]. The analysis underscores the importance of interdisciplinary collaboration, the development of robust electrode materials, and a thorough understanding of mass transport phenomena for realizing the full potential of electrochemical applications in real-world scenarios.

This review's interpretation of the synthesized data underscores the holistic insights gained into electrochemical methods for water treatment, energy conversion, and contaminant separation. The synthesis of CV and GCD data reveals the nuanced performance characteristics of supercapacitors and batteries, guiding efficient design strategies. The integration of conventional water purification methods reflects a pragmatic approach to enhancing water quality for domestic usage, acknowledging the interplay of various purification techniques [34]. Moreover, the elucidation of electrokinetic and electrosorption mechanisms offers a comprehensive understanding of nondestructive contaminant separation processes, offering potential avenues for refining water treatment technologies. The interpretation thus consolidates diverse facets of electrochemical research into a cohesive narrative, informing both academic and practical stakeholders.

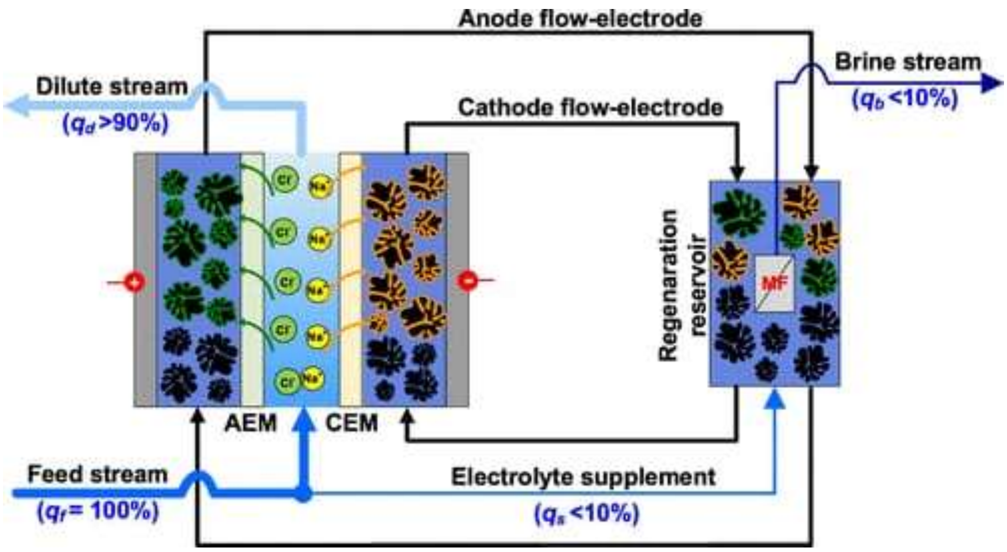

Figure 9. Integrated Flow-Electrode Capacitive Deionization and Microfiltration System for Continuous and Energy-Efficient Brackish Water Desalination. https://pubs.acs.org/doi/10.1021/acs.est.9b04436

The review's interpretation identifies key challnges and pathways for future research. The emphasis on catalyst film formation, trace metal impurities, and voltage dynamics in alkaline electrolyzers highlights potential stumbling blocks in the adoption of these technologies. The comparison of energy consumption metrics exposes the need to optimize electrochemical processes for practical feasibility. This interpretation recognizes that while the field has made significant strides, realizing the full potential of electrochemical applications requires concerted efforts to overcome technical challenges and align theoretical advancements with real-world implementations [35].

The interpretation elucidates the future prospects illuminated by this review. The exploration of zero-gap cells, integrated electrolyzers, advanced materials, and efficient mass transport underscores the research directions that hold promise for elevating the field's impact. As global water scarcity and renewable energy demands intensify, the interpretation emphasizes the timely relevance of electrochemical methods for sustainable water treatment and energy conversion. Furthermore, the review's findings advocate for interdisciplinary collaborations, underscoring the need for seamless integration of engineering, chemistry, and material science to translate theoretical knowledge into practical applications. Overall, this interpretation positions electrochemical methods as pivotal players in addressing pressing environmental and energy challenges [36].

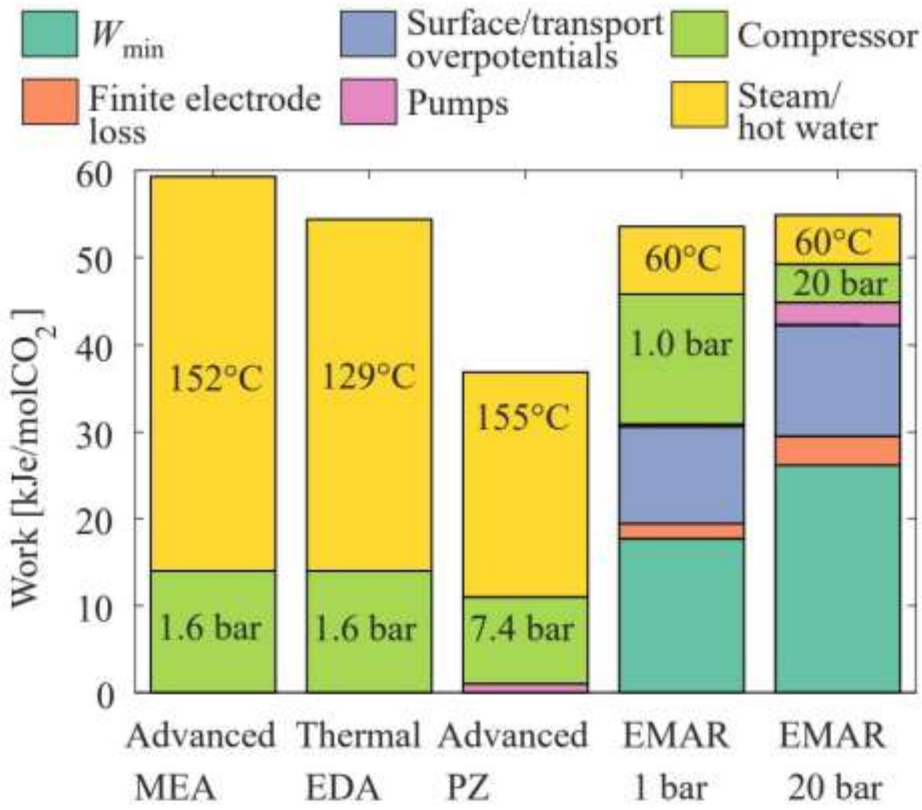

Figure 10. Comparison of published energetics of thermal amine regeneration processes vs. EMAR process. The color for the contributions from the different sources are the same as in previous plots. The temperature of steam/hot water utility needed and the pressure of desorption are marked for each technology, namely the advanced MEA process (NETL, 2013), thermal EDA process (Rabensteiner et al., 2014), and the advanced piperazine process (Lin and Rochelle, 2016).
https://www.osti.gov/servlets/purl/1489146

In comparison to previous studies, this review offers a distinctive advantage by comprehensively synthesizing recent advancements in electrochemical methods for water treatment, energy conversion, and contaminant separation. Unlike earlier reviews that often focused on specific aspects, such as water purification or energy generation, this research integrates multiple facets, providing a more holistic understanding. While some previous reviews primarily discussed theoretical principles, this review delves into practical applications, considering emerging materials, system designs, and efficiency metrics. This comprehensive approach allows for a deeper insight into the challenges and opportunities that the field currently faces.

This research stands out by incorporating detailed comparative analyses between various electrochemical techniques, such as CV and GCD curves, and by comparing energy consumption values in different processes. While prior reviews discussed electrokinetics or electrosorption individually, this study combines both mechanisms, providing a more comprehensive view of contaminant separation [37]. Moreover, the comparison of energy consumption with the thermodynamic limit offers a unique perspective on the efficiency of electrochemical processes. This comparative angle enhances the research's contribution by not only presenting advancements but also evaluating their practical implications [38].

Unlike previous reviews that often concluded with a general summary, this research goes beyond by outlining specific research directions and highlighting the challenges that require immediate attention [39]. While earlier studies might have focused solely on advancements, this review recognizes the gap between theoretical potential and real-world implementation. By identifying the need to address catalyst deposition, trace metal impurities, and voltage dynamics in alkaline electrolyzers, this research paves the way for future investigations. This forward-looking approach sets this review apart, providing a roadmap for researchers and stakeholders to contribute effectively to the field's progression [40].

CONCLUSION

In conclusion, this comprehensive review sheds light on recent advancements in electrochemical methods for water treatment, energy conversion, and contaminant separation. By synthesizing data from diverse sources and applying rigorous analysis, the review provides a cohesive understanding of the field's progress. The integration of cyclic voltammetry and galvanostatic charge-discharge analyses, along with the exploration of various water treatment techniques, underscores the multifaceted nature of electrochemical applications. The elucidation of electrokinetic and electrosorption mechanisms offers insights into innovative contaminant separation strategies. Additionally, the emphasis on challenges in alkaline electrolyzers and the comparison of energy consumption values offer a critical perspective on the field's practical implications. Ultimately, this review not only contributes to the understanding of recent developments but also highlights avenues for future research, aiming to bridge the gap between theoretical potential and real-world implementation of electrochemical methods for sustainable water treatment, energy conversion, and contaminant separation.

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