Mapping the Role of Electrochemistry in Advancing Sustainable Development through Chemistry Education

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Abstract*—The integration of electrochemistry and sustainable development has gained increasing scholarly attention in response to global energy transitions and sustainability agendas. This study maps the evolution, intellectual structure, and emerging themes of research at the intersection of electrochemistry, sustainable development, and chemistry education using a bibliometric approach. A total of 2,204 publications indexed in Scopus between 2000 and 2026 (with 2026 data limited to publications available up to February) were analyzed using Biblioshiny and VOSviewer. The results show a sharp increase in publication output after 2018, reflecting growing interest in sustainability-oriented electrochemical research. Research productivity and citation impact are concentrated in countries such as China and the United States, as indicated by publication counts and citation metrics. Thematic analyses reveal that dominant research areas are driven by technological domains, particularly lithium ion batteries, hydrogen production, electrocatalysis, and machine learning applications. Overlay and trend analyses further indicate the recent expansion of data-driven approaches in electrochemical research. However, only a limited proportion of publications explicitly address educational perspectives, indicating that pedagogical constructs remain peripheral within the field. In this study, transformative educational perspectives refer to approaches that integrate sustainability competencies, systems thinking, and real world problem solving into chemistry learning. The findings suggest a growing imbalance between rapid technological advancement and relatively limited pedagogical integration. This study provides a structured overview of research development and highlights the need for stronger alignment between electrochemical innovation and sustainability-oriented chemistry education.

Keywords*—Bibliometric Analysis; Chemistry Education; Electrochemistry; Renewable Energy; Science Mapping; Sustainable Development.

I. INTRODUCTION

The growing urgency of environmental degradation, climate change mitigation, and sustainable energy transitions has increased attention to the role of science and education in supporting a low-carbon future [1], [2]. Electrochemical systems such as batteries, fuel cells, supercapacitors, and water electrolysis technologies are increasingly important for renewable energy storage and conversion [3]. Because these technologies are grounded in fundamental chemical principles, electrochemistry also offers an important bridge between scientific knowledge, technological innovation, and sustainability education.

Within this study, sustainability-oriented chemistry education refers broadly to chemistry teaching that addresses environmental, social, and economic dimensions of sustainable development, whereas green chemistry education refers more specifically to instructional approaches based on the principles of green chemistry, such as waste prevention, safer chemicals, and resource efficiency [4], [5]. Both perspectives are relevant and complementary, yet they differ in scope. Integrating these perspectives into chemistry curricula is increasingly recognized as an important educational priority [6].

Electrochemistry provides a valuable pedagogical context for this integration because core concepts such as redox reactions, electron transfer, electrode potential, and energy conversion are directly connected to real-world applications including batteries, hydrogen production, corrosion prevention, and environmental remediation [7], [8]. By linking abstract chemical concepts to authentic sustainability issues, electrochemistry learning can strengthen conceptual understanding while fostering awareness of energy, resource, and environmental challenges [9].

Despite this potential, electrochemistry remains one of the most conceptually challenging topics in chemistry education [10], [11]. Prior studies have reported recurring student difficulties in understanding electrochemical cells, oxidation-reduction processes, and the relationship between chemical and electrical energy [12]. Researchers have therefore proposed instructional strategies such as inquiry-based laboratories, multiple representations, simulations, and context-based learning approaches [13], [14]. Although these studies he improved teaching practice, they have generally focused on conceptual achievement and problem solving, with less explicit attention to sustainability learning goals.

At the same time, scholarship related to sustainable and green chemistry education has expanded substantially [15],

[16]. Researchers have explored curriculum redesign, safer laboratory practices, and the inclusion of renewable energy topics in chemistry courses [17]. However, the extent to which electrochemistry has been systematically positioned as a central vehicle for sustainability-oriented chemistry education remains unclear [18], [19]. Relevant studies are dispersed across chemistry education, science education, engineering education, and energy-related instructional contexts, creating a fragmented view of the field [20], [21].

Previous reviews have mainly emphasized pedagogical strategies, conceptual difficulties, or specific instructional interventions rather than quantitatively mapping the broader research landscape [22], [23]. While such reviews provide useful insights, publication trends, collaboration networks, citation structures, and thematic development have been less systematically mapped across time [24], [25]. As a result, it remains difficult to identify how the field has evolved, where influential contributions are concentrated, and which emerging areas warrant further attention.

Bibliometric analysis offers a quantitative approach for examining the development of a research field through publication patterns, citation relationships, authorship networks, and keyword structures [26]. Compared with narrative reviews, bibliometric analysis can reveal macro-level intellectual structures, collaboration patterns, and thematic evolution that may be less visible through descriptive synthesis alone [27]. Applying this approach to literature connecting electrochemistry, chemistry education, and sustainable development can therefore provide evidence-based insights for future curriculum innovation, interdisciplinary collaboration, and research planning.

In this study, the literature boundary includes peer-reviewed publications indexed in Scopus that address electrochemistry within chemistry, science, or closely related engineering education contexts where teaching and learning are central concerns. Purely technical electrochemical studies without educational relevance are excluded. Accordingly, this study aims to map the global research landscape at the intersection of electrochemistry, sustainable development, and chemistry education through a bibliometric analysis of peer-reviewed publications indexed in Scopus. The study contributes by identifying publication trajectories, leading contributors, collaboration structures, and evolving research themes, thereby providing actionable insights for curriculum designers, chemistry educators, electrochemistry researchers, and policy stakeholders. To achieve these objectives, the study addresses the following research questions:

RQ1. How have publication trends in electrochemistry education for sustainable development evolved over the past two decades?

RQ2. Who are the major contributors (countries, institutions, and authors), and how are their collaboration networks structured?

RQ3. How have dominant, emerging, and declining themes developed within the literature on electrochemistry in chemistry education for sustainable development?

RQ4. What research gaps and future opportunities can be identified from the structural and thematic mapping of the literature?

II. Methodology

This study employed a bibliometric research design to examine the development of scholarly literature at the intersection of electrochemistry, sustainable development, and chemistry education. Bibliometric analysis is widely used to evaluate publication growth, citation impact, collaboration patterns, and thematic evolution within a defined research domain [28]. Given the interdisciplinary nature of this topic, the approach was considered appropriate for identifying both performance indicators and structural trends in the literature.

Scopus was selected as the primary data source because of its broad international coverage of peer-reviewed journals across chemistry, engineering, environmental science, and education disciplines [29]. Although Scopus provides extensive indexing, the use of a single database may omit publications indexed exclusively in Web of Science, ERIC, or regional databases. This limitation should be considered when interpreting the findings.

The literature search was conducted in February 2026, and therefore the 2026 records represent partial-year data rather than a complete annual publication count**. The search was performed using the Scopus Advanced Search interface in the title, abstract, and keyword fields (TITLE-ABS-KEY). The complete Boolean search string used in this study was:

(TITLE-ABS-KEY(electrochem OR "voltaic cell" OR "galvanic cell" OR electrolysis) AND TITLE-ABS-KEY(education OR teaching OR learning OR pedagogy OR curriculum) AND TITLE-ABS-KEY(sustainab* OR "green chemistry" OR renewable OR energy)) AND (LIMIT-TO(DOCTYPE,"ar") OR LIMIT-TO(DOCTYPE,"re"))*

The three conceptual term clusters represented electrochemistry, education, and sustainability, respectively. Only records simultaneously matching all three clusters were retrieved, ensuring alignment with the study focus. The search was limited to journal articles and review articles to maintain academic rigor. No Scopus subject-area restriction was applied at the search stage; however, records were screened to retain studies with clear relevance to teaching, learning, curriculum, or educational practice. Thus, purely technical electrochemistry studies without educational relevance were excluded.

The initial search retrieved 2,815 records. Screening and eligibility procedures were conducted using an adapted PRISMA-style workflow to enhance transparency in record selection. Although PRISMA was originally developed for systematic reviews, its identification–screening–inclusion logic is increasingly adopted in bibliometric studies to document dataset refinement. Duplicate records (n = 2) were first removed. After title and metadata screening, irrelevant records were excluded (n = 4). Reports not retrievable in full metadata form were removed (n = 18). During eligibility assessment, non-article or non-review records (n = 490) and non-English publications (n = 115) were excluded. The final dataset comprised 2,204 documents. The full selection process is presented in Fig. 1.

All educational levels were considered eligible, including school-level, undergraduate, graduate, vocational, and informal educational contexts, provided that teaching or learning constituted a central component of the publication.

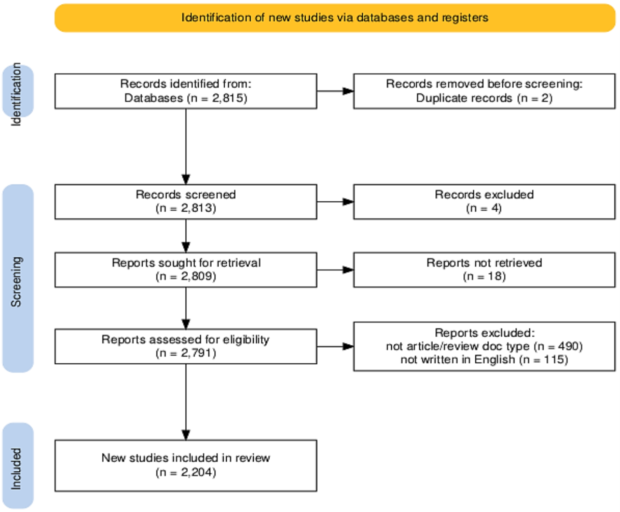

Fig. 1. PRISMA flow for record selection

Prior to analysis, data cleaning procedures were undertaken to improve consistency. Author keywords and index keywords were standardized by merging singular/plural variants, spelling differences, abbreviations, and synonymous forms (e.g., "Li-ion battery" and "lithium ion battery"; "fuel cell" and "fuel cells"). Generic non-informative terms were also removed where necessary.

The bibliometric analysis was conducted using Biblioshiny (the web interface of the Bibliometrix package in R) and VOSviewer. Biblioshiny was primarily used for descriptive performance analysis, including annual publication trends, leading countries, productive institutions, source journals, authorship productivity, and citation indicators. VOSviewer was used for science mapping and network visualization, including co-authorship, co-citation, and keyword co-occurrence networks.

Keyword co-occurrence analysis was performed to identify dominant and emerging themes. A minimum threshold of 35 occurrences was applied to improve readability and interpretability of the network by retaining only highly recurrent terms. This threshold was selected after preliminary trials with lower cut-offs produced dense and fragmented maps with limited interpretive clarity. Keywords below the threshold were excluded from visualization but remained part of the broader dataset.

The full counting method was employed, meaning that each keyword occurrence was counted equally across publications. This approach was chosen because the study aimed to capture the visibility and recurrence of themes rather than proportionally weighting terms by the number of co-occurring keywords or co-authors. Consequently, highly collaborative publications may contribute more strongly to network density than under fractional counting.

Manual screening was conducted by the researcher using predefined inclusion and exclusion criteria based on document type, language, and educational relevance. Ambiguous cases were rechecked through abstract review to ensure consistency.

By integrating performance analysis and science mapping techniques, this methodological framework provides both descriptive and structural insights into the evolution of research on the role of electrochemistry in advancing sustainable development through chemistry education.

III. Results and Discussion

The bibliometric mapping conducted in this study provides a comprehensive overview of global research developments at the intersection of electrochemistry, sustainable development, and chemistry education. The results are structured in alignment with the four research questions guiding this investigation. First, the analysis examines how publication trends have evolved over the past two decades, highlighting growth patterns and the overall development of the field. Second, the study explores how major contributors, including countries, institutions, and authors, have shaped the research landscape and how their collaboration networks are structured. Third, thematic and keyword-based analyses are employed to explain how dominant and emerging research themes have developed within the literature. Finally, through structural and thematic mapping, the analysis identifies how research gaps and underexplored areas can be discerned, offering strategic insights for advancing electrochemistry education in support of sustainable development. Together, these findings provide a systematic understanding of the field's evolution and its future research potential.

A. *Evolution of Publication Trends*

The analysis of annual scientific production indicates a clear expansion of research at the intersection of electrochemistry, sustainable development, and chemistry education over the past two decades. As shown in Fig. 2, publication output remained relatively low and stable from 2000 to approximately 2016, generally fluctuating at single-digit or low double-digit levels. This pattern suggests that the topic had not yet developed into a consolidated research area, with publications still dispersed across adjacent disciplines.

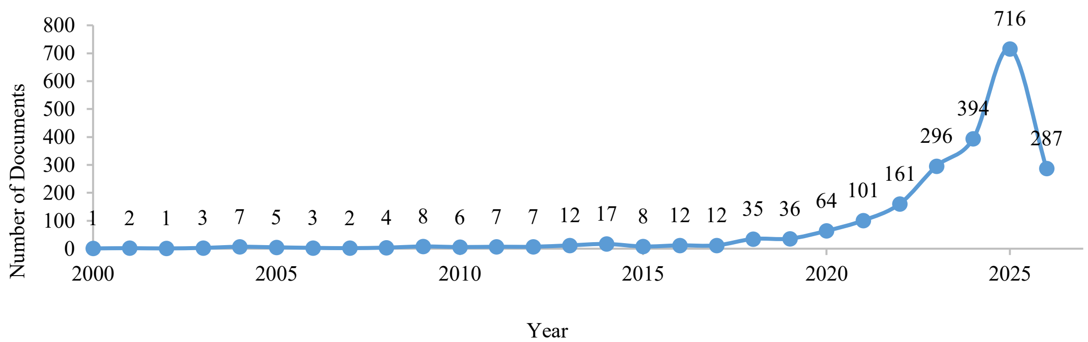

Fig. 2. Annual scientific production

TABLE I. MOST GLOBAL CITED DOCUMENTS

Paper	DOI	Total Citations	TC per Year
Van De Burgt Y, 2017, Nat Mater	10.1038/NMAT4856	1627	163
Hwang J, 2017, Science	10.1126/science.aam7092	1581	158
Chatenet M, 2022, Chem Soc Rev	10.1039/d0cs01079k	1484	297
Zhong M, 2020, Nature	10.1038/s41586-020-2242-8	1308	187
Van De Burgt Y, 2018, Nat Electron	10.1038/s41928-018-0103-3	965	107
Li Y, 2019, Chem Soc Rev	10.1039/c9cs00162j	783	98
Batchelor Taa, 2019, Joule	10.1016/j.joule.2018.12.015	773	97
Tran K, 2018, Nat Catal	10.1038/s41929-018-0142-1	772	86
Yu D, 2022, Mol Cancer	10.1186/s12943-022-01509-9	720	144
Chayambuka K, 2018, Adv Energy Mater	10.1002/aenm.201800079	649	72
Adenusi H, 2023, Adv Energy Mater	10.1002/aenm.202203307	551	138
Wang Y, 2020, Energy AI	10.1016/j.egyai.2020.100014	446	64
Wang J, 2020, J Power Sources	10.1016/j.jpowsour.2020.227794	418	60
Saba S, 2018, Int J Hydrogen Energy	10.1016/j.ijhydene.2017.11.115	415	46

A sustained growth phase began around 2017, followed by a sharper increase from 2020 onward. The acceleration during 2020–2025 likely reflects several converging factors, including growing global attention to sustainable development, rapid advances in battery and hydrogen technologies, and increasing curricular interest in energy-transition topics within science education education [30], [31]. The strongest growth occurred in 2024 and 2025, reaching a peak of 716 publications in 2025.

The lower count recorded for 2026 should not be interpreted as a decline in scholarly interest. Because the database search was conducted in February 2026, the 2026 values represent partial-year indexed records and are affected by normal indexing delays. Fig. 2 therefore reflects incomplete annual coverage for the most recent year.

Overall, the temporal pattern indicates that this field has moved from a peripheral topic in the early 2000s to a rapidly expanding interdisciplinary domain in recent years. The growth trajectory also suggests increasing recognition of electrochemistry as a relevant context for sustainability-related chemistry education.

Further insight into the intellectual structure of this growth is provided by citation analysis. Table I presents the most globally cited publications retrieved in the dataset. Highly cited works such as Van De Burgt (2017), Hwang (2017), and Chatenet (2022) demonstrate the strong visibility of research associated with electrochemical materials, energy systems, and catalytic applications. Several additional influential papers were published in high-impact outlets such as Nature, Nature Electronics, Joule, Advanced Energy Materials, and Journal of Power Sources.

These citation patterns indicate that the knowledge base of the field has been shaped substantially by advances in electrochemical energy and materials research, with educational applications emerging alongside these developments rather than independently from them [32]. In this sense, technological innovation appears to provide many of the real-world contexts later translated into teaching, curriculum, or sustainability-oriented discussions [33].

However, Table I should be interpreted cautiously. Bibliometric retrieval using broad interdisciplinary keywords may occasionally capture highly cited records whose educational relevance is indirect. Such cases should be manually verified when interpreting top-cited outputs.

Taken together, the publication trend in Fig. 2 and the citation profile in Table I suggest that the field is developing through the convergence of sustainability priorities, electrochemical technological progress, and growing educational interest. A key implication is that future scholarship should move beyond using technology merely as context and more explicitly investigate how electrochemistry can support curriculum innovation, systems thinking, and sustainability competencies in chemistry education [34].

B. Major Contributors and Collaboration Stuctures

The distribution of research output in this field is highly concentrated geographically, with a small number of countries accounting for a substantial share of publications and citations. As shown in Table II, China leads both publication volume (2,249 documents) and total citations (16,685), followed by the United States with 1,002 documents and 12,937 citations. These results indicate that the global research landscape is strongly shaped by countries with major investments in electrochemical technologies, renewable energy, and advanced manufacturing [35], [36].

However, total citation counts should be interpreted alongside publication volume. Using a simple normalized indicator (citations per paper), the United States (≈12.9 citations/article) exceeds China (≈7.4 citations/article), suggesting comparatively higher average impact per publication. Other countries such as Canada (≈23.6), Germany (≈15.4), and the Netherlands (≈11.2) also show strong citation efficiency despite lower output volumes. This suggests that influence in the field is not determined solely by productivity, but also by publication visibility, collaboration reach, and citation intensity.

The collaboration network in Fig. 3 further clarifies these patterns. China and the United States appear as the two largest and most connected nodes, indicating their central role in international knowledge exchange. China is strongly linked with several Asian and Middle Eastern countries, whereas the United States is embedded in a dense network connecting Europe, North America, and Oceania. This dual-hub structure suggests two major collaboration spheres that jointly organize much of the field's international activity [37].

TABLE II. COUNTRY CONTRIBUTION IN PUBLICATION AND CITATION

Country Rank	Country	N of Citations	Country	N of Articles
1	China	16685	China	2249
2	USA	12937	USA	1002
3	Korea	3444	India	460
4	Canada	3321	South Korea	397
5	Germany	3050	Germany	198
6	Netherlands	2221	United Kingdom	186
7	India	2138	Canada	141
8	United Kingdom	1451	Saudi Arabia	139
9	Denmark	1419	Australia	134
10	France	1370	Japan	118

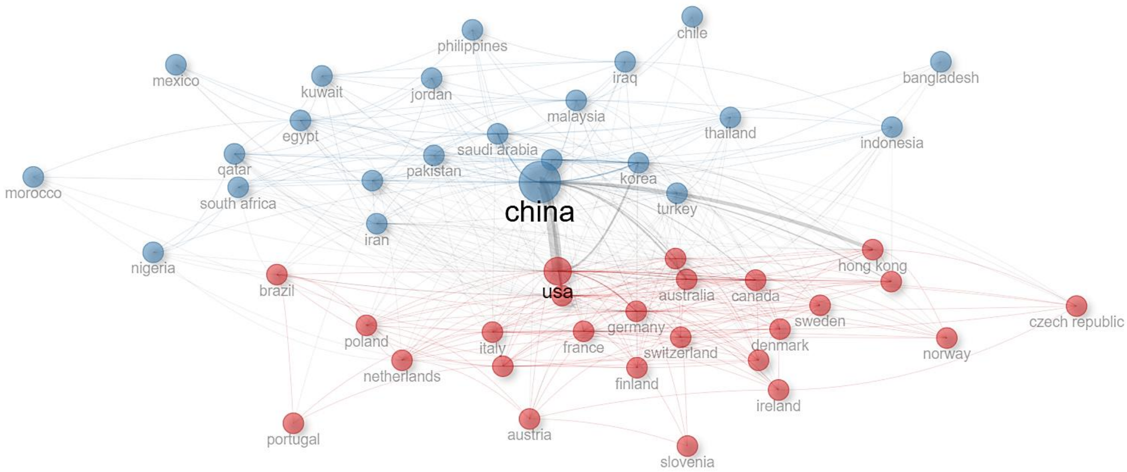

Fig. 3. Collaboration network

Several mid-level contributors, including South Korea, Germany, Canada, the United Kingdom, and India, also play important roles. South Korea and Germany combine moderate output with relatively strong citation performance, while India demonstrates substantial productivity but lower citation intensity relative to leading Western countries. This may reflect differences in journal placement, network centrality, or the maturity of international collaborations rather than research quality alone [38].

At the author and institutional level, Table III indicates further concentration. Because several surnames are common (e.g., Wang, Li, Zhang, Liu), full author names or standardized initials should be reported in the final manuscript to avoid ambiguity. The leading affiliations include Tsinghua University, Tianjin University, Huazhong University of Science and Technology, Shanghai Jiao Tong University, Peking University, MIT, and the University of California, all of which are research-intensive institutions with strong engineering or materials-science profiles.

Notably, specialized teacher education institutions or faculties of education appear less prominent among the leading affiliations. This pattern suggests that scholarship in this area is still largely generated within science, engineering, and technology-oriented environments rather than within education-centered research communities. As a result, pedagogical innovation may lag behind technological contextualization [39].

The list of leading publication sources reinforces this interpretation. While the Journal of Chemical Education appears among the core outlets, many influential sources are technology-focused journals such as International Journal of Hydrogen Energy, Journal of Energy Storage, Journal of Power Sources, Applied Energy, and Advanced Materials. This indicates that the field remains interdisciplinary, but its publication core is more strongly aligned with energy and materials research than with educational theory.

Fig. 4 (corresponding author countries) provides additional insight into domestic versus international collaboration patterns through Single Country Publications (SCP) and Multiple Country Publications (MCP). China shows a predominance of SCP output, indicating a strong domestic research ecosystem capable of sustaining high productivity internally. In contrast, the United States shows a more balanced SCP–MCP profile, suggesting greater dependence on or openness to cross-national collaboration. Several European countries also display relatively higher MCP proportions, consistent with established multinational research frameworks [40].

These contrasting profiles imply two complementary models of research advancement: (1) scale-driven national productivity, represented most clearly by China; and (2) network-driven international influence, represented by the United States and several European countries. Taken together, these findings reveal a field characterized by geographic concentration, hub-based collaboration networks, and strong participation from technologically oriented institutions [41], [42]. For future development, broader involvement of chemistry education scholars, teacher-training institutions, and researchers from underrepresented regions may help diversify research agendas and strengthen pedagogical depth.

TABLE III. MOST RELEVANT CONTRIBUTORS IN PUBLICATION

Category	Contributor
Most relevant authors	Wang Y, Li Y, Zhang X, Liu Y, Wang X, Li J, Wang J, Zhang Y, Zhang H, Li X, Liu X, Wang Z, Chen Y, Liu J, Li Z, Yang Y, Zhang Z, Zhang J, Zhang L, Wang H
Most relevant affiliations	Tsinghua University, College of Engineering, Tianjin University, Huazhong University of Science and Technology, MIT School of Engineering, Shanghai Jiao Tong University, University of California, Central South University, Khalifa University, Peking University, University of Chinese Academy of Sciences, City University of Hong Kong, The Hong Kong Polytechnic University, National University of Singapore
Most relevant sources	Journal of Chemical Education, International Journal of Hydrogen Energy, Journal of Energy Storage, Journal of Materials Chemistry, Journal of Power Sources, Applied Energy, Journal of The American Chemical Society, Nature Communications, Advanced Materials, Chemical Engineering Journal, Energies, Energy Conversion and Management, Journal of Physical Chemistry, ACS Applied Materials and Interfaces

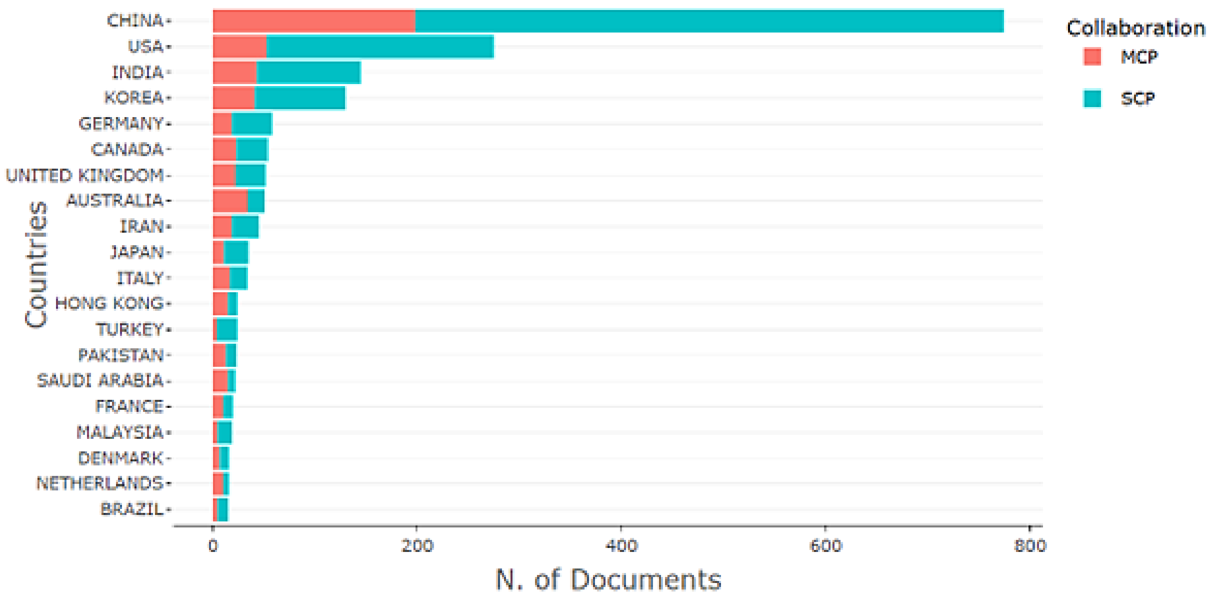

Fig. 4. Corresponding author's countries

C. *Thematic Development and Emerging Areas*

The thematic structure of the field was examined through keyword co-occurrence analysis using VOSviewer (Fig. 5), complemented by overlay visualization (Fig. 6) and trend-topic analysis (Fig. 7). Because these three figures partially address similar patterns, they are interpreted here in an integrated manner to avoid redundancy. Collectively, the results show that research at the intersection of electrochemistry, sustainable development, and chemistry education is organized around several dominant themes, with technological applications occupying the most central positions.

In Fig. 5, machine learning appears as one of the largest and most connected nodes, linking terms such as lithium-ion batteries, energy storage, forecasting, and learning systems. This indicates the growing integration of artificial intelligence and predictive modelling into electrochemical research, particularly for materials optimization, battery diagnostics, and energy-system performance [43]. Similar trends have been reported in broader energy bibliometric studies, where data-driven methods increasingly shape sustainable technology development [44].

A second major cluster is centered on hydrogen production, electrolysis, renewable energy, and electrocatalysis. The prominence of these terms reflects increasing global attention to green hydrogen, water splitting, and low-carbon fuel systems. A third cluster is associated with lithium-ion batteries, solid electrolytes, electrochemical impedance spectroscopy, and state of health, indicating the continuing importance of battery technologies within sustainability-oriented research. Together, these patterns suggest that sustainability in the current literature is most often operationalized through energy storage, hydrogen systems, and optimization technologies.

In contrast, explicitly educational terms such as hands-on learning, laboratory instruction, teaching, and curricula are present but comparatively peripheral. Their smaller node size and weaker connectivity suggest that educational themes are less structurally central than technological themes. This interpretation should be considered alongside the keyword threshold applied in the study (minimum occurrence = 35), which favors high-frequency terms and may underrepresent smaller but meaningful pedagogical topics. Lower thresholds would likely reveal a richer educational vocabulary.

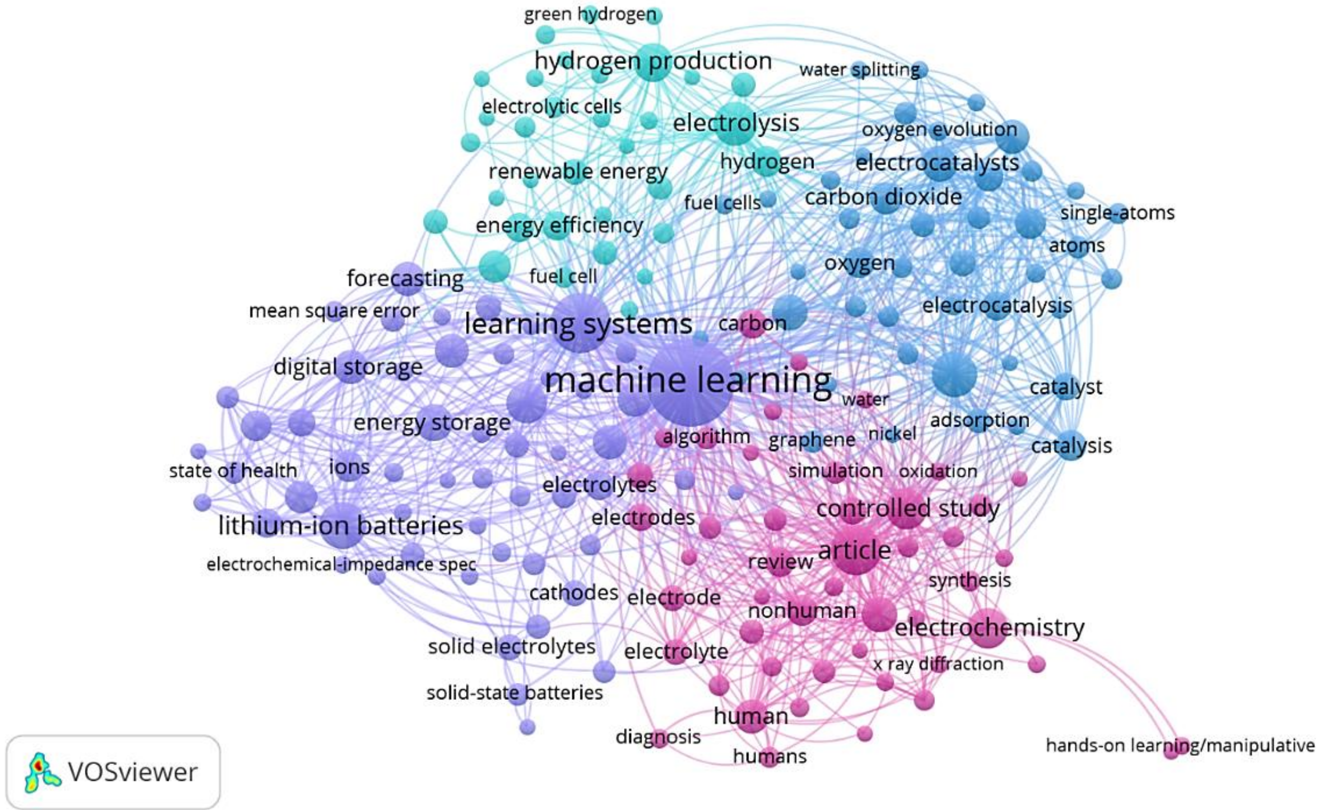

Fig. 5. Network visualization

The overlay visualization in Fig. 6 provides temporal evidence for thematic change. Earlier average-year terms (darker colors) include electrochemistry, catalysis, adsorption, and oxygen evolution, reflecting a stronger early emphasis on fundamental mechanisms and materials research. More recent average-year terms (lighter colors, approximately 2024.0–2024.5) include machine learning, hydrogen production, renewable energy, forecasting, and digital storage. Thus, the recent expansion of the field appears strongly associated with digitalization and next-generation energy technologies rather than with new pedagogical frameworks [45].

Battery-related keywords such as lithium-ion batteries remain prominent across time, suggesting continuity rather than replacement. In other words, the field has diversified from a battery-dominated focus toward a broader portfolio that now includes hydrogen systems and computational intelligence.

Trend-topic analysis (Fig. 7) further supports this chronological development and suggests three broad phases in the evolution of the field. The early phase (2003–2010) was dominated by themes such as chemical engineering and electrochemical engineering, indicating a primarily industrial and applied research orientation. During the transitional phase (2011–2018), terms such as education, teaching, students, curricula, and laboratory instruction became more visible, reflecting the growing incorporation of electrochemistry into formal learning contexts. In the recent phase (2019–2025), the literature shows a rapid rise in topics such as machine learning, learning systems, computational efficiency, renewable energy resources, and lithium-ion batteries, suggesting an increasing emphasis on digitalization, sustainability, and advanced energy technologies. This sequence suggests that educational integration emerged after the technological base had already matured, and recent growth is again being accelerated by digital and sustainability technologies [46].

An important implication is that electrochemistry offers strong real-world contexts for chemistry education, particularly through batteries, hydrogen production, and energy transition topics. However, the bibliometric structure also indicates opportunities for stronger pedagogical development. Terms such as sustainability competencies, systems thinking, socio-scientific reasoning, teacher professional development, curriculum design, and assessment are not yet prominent in the current thematic core.

Future research could therefore move beyond using technology merely as context and examine how electrochemistry learning can intentionally develop sustainability literacy, decision-making skills, interdisciplinary reasoning, and transformative action competencies. This would strengthen the educational contribution of the field while preserving its scientific relevance [44], [47].

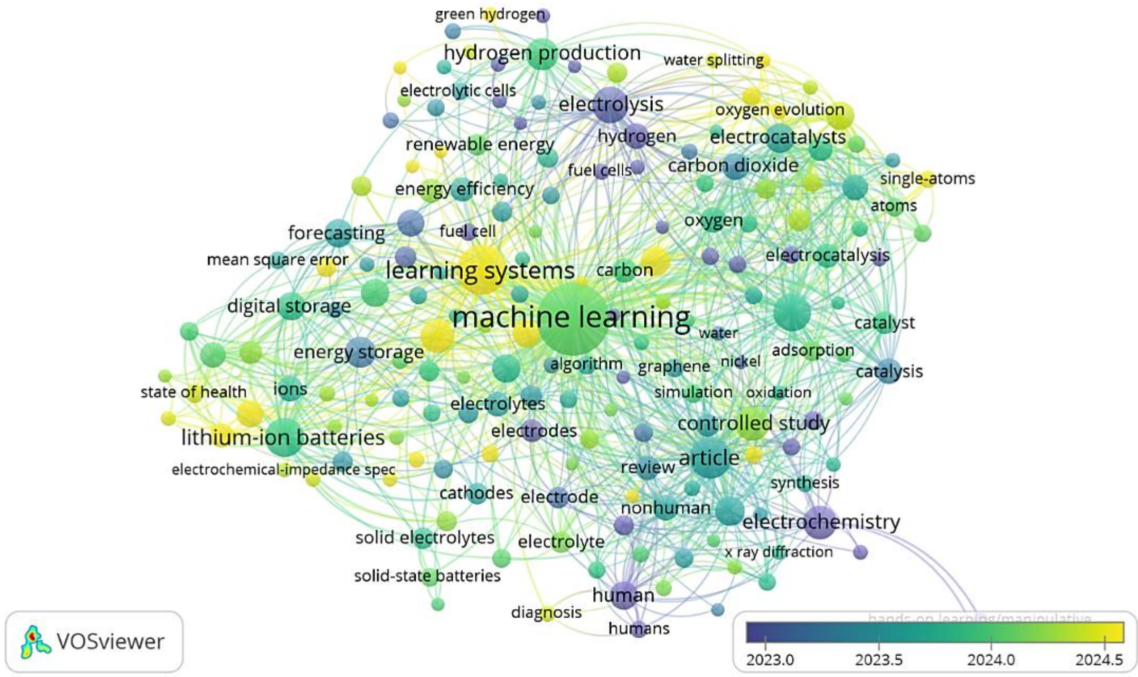

Fig. 6. Overlay visualization

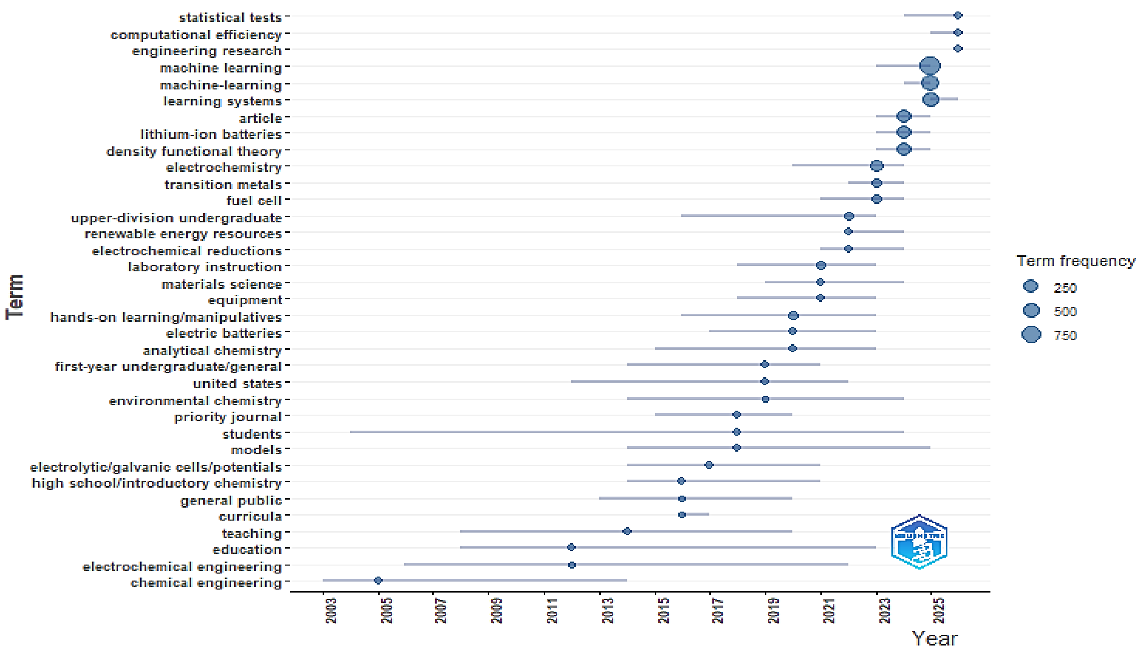

Fig. 7. Trend topics

D. Research Gaps and Future Directions

The thematic map in Fig. 8 provides a structural overview of research priorities by positioning themes according to centrality (relevance to the broader field) and density (degree of internal development). This allows identification of motor themes, basic themes, niche themes, and emerging or declining themes. Rather than interpreting these quadrants deterministically, they should be read as indicators of relative thematic maturity and connectivity.

In the motor themes quadrant (high centrality, high density), the dominant cluster includes article, density functional theory, and controlled study. These terms indicate that highly connected and mature areas of the field are strongly associated with experimental, computational, and methodological research traditions. This finding is consistent with earlier network analyses showing the prominence of materials science, modelling, and performance-oriented electrochemical research.

The basic themes quadrant (high centrality, lower density) includes machine learning, learning systems, and related AI terms. Their location suggests that these topics are already important to the overall field but are still evolving conceptually. In practical terms, artificial intelligence has become a major research driver, yet its educational implications remain comparatively underdeveloped. Future studies could examine how machine-learning-based electrochemistry can be translated into classroom modelling tasks, inquiry learning, or data-literacy development in chemistry education.

A bridging cluster containing lithium-ion batteries, energy storage, and deep learning appears near the center-right region of the map. This position indicates substantial relevance with moderate internal consolidation. These themes appear to connect sustainability discourse with technological innovation, making them promising contexts for curriculum integration related to renewable energy, battery literacy, and resource sustainability.

In the niche themes quadrant (low centrality, high density), terms such as electrochemistry, electrochemical analysis, and human are present. These themes appear internally developed but less connected to the wider field. This may indicate specialized research streams that have matured independently but are not yet strongly integrated into broader sustainability or education conversations.

Of particular interest is the emerging or declining themes quadrant (low centrality, low density), where green chemistry and educational terms such as hands-on learning/manipulatives, laboratory instruction, and upper-division undergraduate appear. This position does not necessarily imply decline; rather, it may indicate either early-stage development or limited integration within the current dataset. Because bibliometric thematic maps are sensitive to keyword frequency and clustering parameters, these themes should be interpreted cautiously.

Nevertheless, the placement of these pedagogical and green-chemistry themes suggests an important gap: while sustainability is frequently represented through batteries, hydrogen systems, and optimization technologies, curriculum design, laboratory pedagogy, sustainability competencies, and transformative learning remain less central in the field’s current structure [48], [49].

The Sankey diagram in Fig. 9 complements this interpretation by showing associations among countries, authors, and dominant keywords. China contributes the largest visible flow, followed by the United States and several other countries. Many of the strongest connections are linked to terms such as machine learning, density functional theory, electrochemical impedance spectroscopy, artificial intelligence, and optimization.

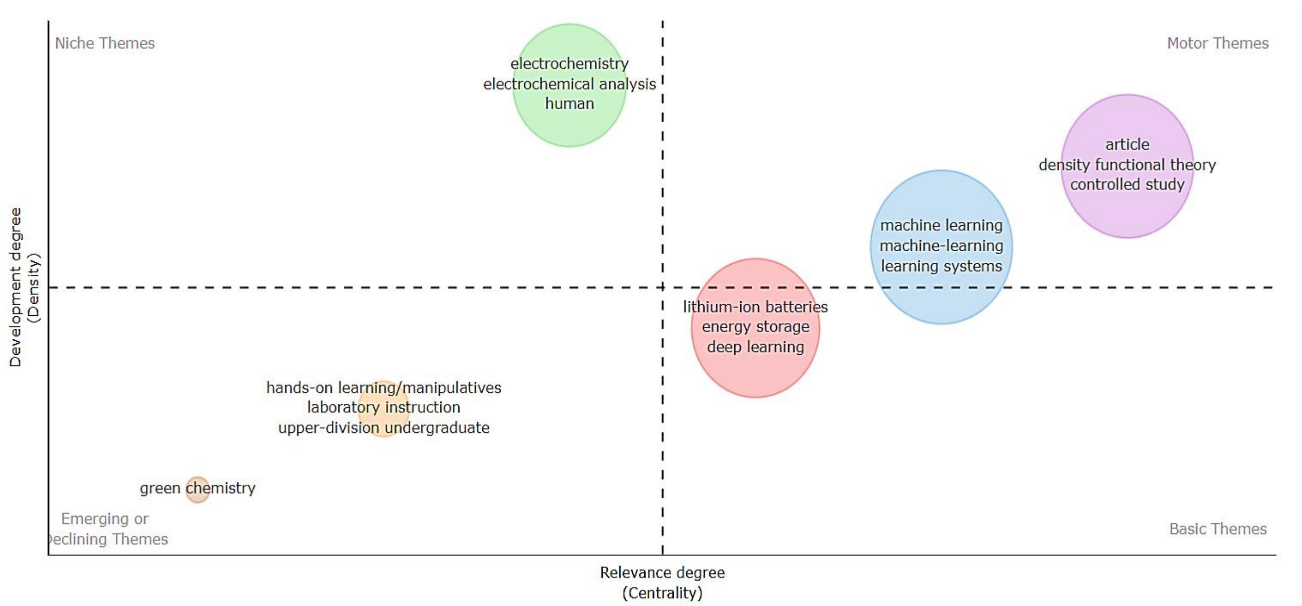

Fig. 8. Thematic map

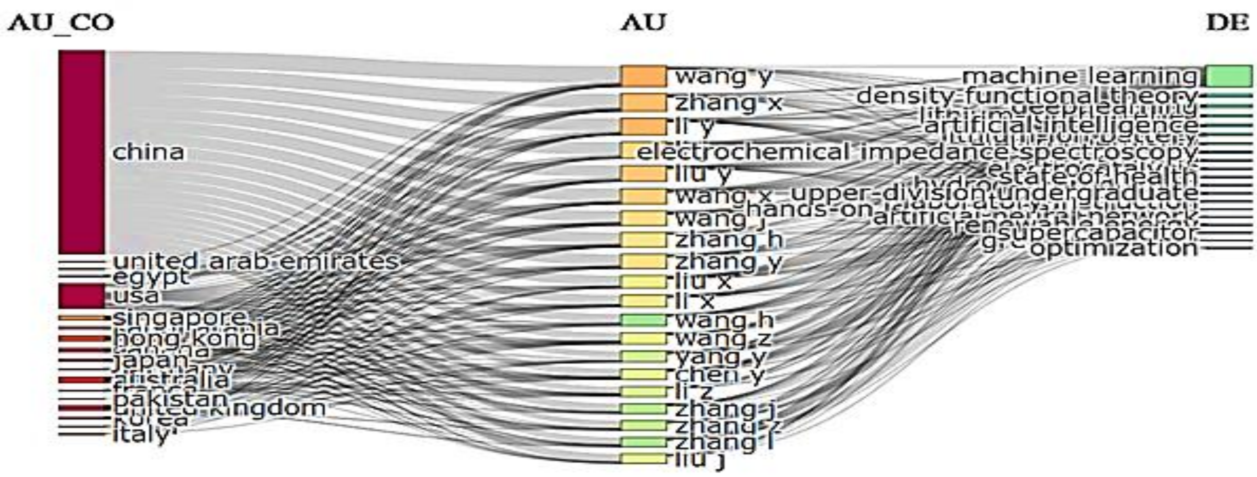

Fig. 9. Sankey diagram

These flows should be interpreted as co-occurrence patterns rather than causal evidence that specific countries "drive" particular themes. Instead, the diagram suggests that countries with high publication volume are more strongly associated with currently dominant technological keywords. Educationally oriented keywords are comparatively less visible in the Sankey structure, again indicating that pedagogical themes occupy a smaller share of the high-frequency research landscape [50], [51].

Taken together, Fig. 8 and Fig. 9 indicate a field that is scientifically dynamic but educationally uneven. Strong growth is occurring in computational electrochemistry, energy storage, hydrogen production, and AI-assisted optimization, yet these advances are not always matched by equivalent development in teaching models, curriculum frameworks, or sustainability learning outcomes.

Based on these findings, several future directions are recommended. Sustainability competencies should be more explicitly integrated into electrochemistry instruction, including systems thinking, ethical reasoning, life-cycle awareness, and evidence-based decision making. Batteries, fuel cells, corrosion, and hydrogen systems can be utilized as curriculum contexts not only as technical topics, but also as socio-scientific case studies relevant to contemporary sustainability challenges. Stronger collaboration between engineering researchers and chemistry education scholars is also needed to connect technological advances with learning theory and pedagogical innovation. In addition, further research should focus on teacher professional development and classroom implementation, particularly at the secondary and undergraduate levels. Greater participation from underrepresented regions and institutions would help diversify perspectives on sustainability challenges and local educational needs. Finally, future studies should examine the responsible use of artificial intelligence in chemistry education, including data interpretation, simulation-based learning, and critical reflection on environmental impacts [52].

Finally, these results should be interpreted alongside the limitations of bibliometric analysis. The dataset was derived from a single database, limited to English-language indexed publications, and influenced by keyword selection and threshold settings. Therefore, some emerging pedagogical themes may be less visible than they are in practice.

IV. Conclusion

Based on the four research questions, several key conclusions can be synthesized. First, in relation to RQ1, publication output remained relatively limited until the mid-2010s but increased substantially after 2018, with particularly rapid growth during 2020–2025. This pattern indicates growing scholarly attention to the role of electrochemistry in sustainability and educational contexts, although recent expansion has been driven more strongly by technology-oriented topics than by pedagogical research. Second, regarding RQ2, the field is led primarily by China and the United States in terms of publication volume, citation impact, and collaboration centrality. International collaboration networks are strongly hub-based, while participation from many regions and education-focused institutions remains comparatively limited.

Third, in response to RQ3, thematic analyses identified three dominant pillars of research: energy storage systems, particularly lithium-ion batteries; hydrogen and electrolysis technologies; and machine-learning-enabled optimization. Recent developments also show increasing emphasis on digitalization and renewable energy transitions. However, educational themes such as curriculum reform, systems thinking, assessment, and teacher development remain less central in the current thematic structure. Fourth, regarding RQ4, structural mapping reveals a clear imbalance between rapid technological advancement and slower educational integration. Sustainability is frequently framed through technical innovation rather than through transformative learning approaches, competency development, or classroom implementation.

Taken together, these findings suggest that the next phase of research should focus more explicitly on translating electrochemical innovation into meaningful chemistry education for sustainable development. Priority areas include the development of competency-based electrochemistry curricula, teacher professional development, responsible integration of artificial intelligence, broader international collaboration, and stronger partnerships between engineering researchers and chemistry education scholars.

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