

A bibliometric analysis of learning environments in chemistry education

Nataliia Yu. Lykhopavlo

Kryvyi Rih State Pedagogical University, 54 Universytetskyi Ave., Kryvyi Rih, 50086, Ukraine

Abstract. This study presents a comprehensive bibliometric analysis of research on learning environments in chemistry education, examining global trends and patterns from a corpus of 988 publications indexed in the Scopus database as of July 2025. The research employed bibliometric techniques using VOSviewer to analyse publication trends, collaboration networks, and thematic evolution in the field. The analysis revealed a significant increase in research output since 2014, with notable acceleration following the COVID-19 pandemic. Three major research clusters emerged from keyword co-occurrence analysis: technology-enhanced learning environments, inquiry-based pedagogical approaches, and assessment methodologies. The United States (287 publications, 29%), China (156 publications, 16%), and Germany (98 publications, 10%) lead in publication output, while emerging research centres in Turkey and developing countries show increasing contributions. The findings indicate a paradigm shift from traditional laboratory-based instruction to digital and hybrid learning environments, with artificial intelligence and virtual reality emerging as transformative technologies.

Keywords: bibliometric analysis, chemistry education, learning environments, VOSviewer, research trends, digital learning, science education

1. Introduction

1.1. Background and context

The landscape of chemistry education has undergone profound transformations over the past decade, driven by technological innovations, pedagogical reforms, and global events that have reshaped educational paradigms [6, 37]. Learning environments in chemistry education have evolved from traditional classroom and laboratory settings to encompass digital platforms, virtual laboratories, and hybrid instructional models that integrate multiple modalities of engagement. This evolution reflects broader trends in educational technology adoption and the increasing recognition that effective chemistry learning requires environments that support inquiry, collaboration, and authentic scientific practices [33].

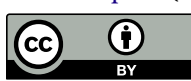
Contemporary chemistry education faces unique challenges that distinguish it from other scientific disciplines. The abstract nature of chemical concepts, the necessity for three-dimensional molecular visualisation, and the critical role of laboratory experiences create specific demands for learning environment design [16]. These challenges have prompted researchers to investigate how different environmental configurations support or hinder student learning, leading to a rich body of literature that spans traditional face-to-face instruction, technology-mediated learning, and innovative hybrid approaches. The integration of digital tools has particularly accelerated in recent years, with virtual reality, augmented reality, and artificial intelligence emerging as transformative technologies in chemistry education [8, 19].

The COVID-19 pandemic served as an unprecedented catalyst for change in chemistry education, forcing rapid adoption of remote and hybrid learning models worldwide

✉ lykhopavlo@knvk129.dp.ua (N. Yu. Lykhopavlo)



Science
Education
Quarterly



© Copyright for this article by its authors, published by the Academy of Cognitive and Natural Sciences. This is an Open Access article distributed under the terms of the Creative Commons License Attribution 4.0 International (CC BY 4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

[13]. This global disruption not only accelerated existing trends toward digitalisation but also prompted fundamental questions about the nature of effective chemistry learning environments. Educators and researchers were compelled to reimagine laboratory experiences, develop new assessment strategies, and create engaging online environments that could replicate the collaborative and hands-on aspects of traditional chemistry instruction. The pandemic's impact extended beyond temporary adaptations, leading to permanent changes in how chemistry education is conceptualised and delivered [40].

Understanding the evolution and current state of research on chemistry learning environments requires systematically analysing the scholarly literature. Bibliometric analysis provides a powerful lens to examine research trends, identify influential works and authors, map collaboration networks, and detect emerging themes [18]. Such analysis is particularly valuable in rapidly evolving fields like chemistry education, where technological innovations and pedagogical approaches continuously reshape the research landscape. By mapping the intellectual structure of the field, bibliometric studies can help educators make evidence-based decisions about learning environment design.

1.2. Research gap and justification

While numerous studies have examined specific aspects of chemistry learning environments, comprehensive bibliometric analyses of this field remain scarce. Previous bibliometric studies in chemistry education have typically focused on narrow topics such as laboratory instruction, assessment methods, or specific technologies, without providing a holistic view of how learning environment research has evolved. This fragmentation limits our understanding of the field's intellectual structure, the relationships between different research streams, and the emergence of new paradigms in chemistry education. A comprehensive bibliometric analysis can address these limitations by systematically mapping the research landscape.

The rapid pace of technological change in education creates an urgent need for updated analyses that capture recent developments in chemistry learning environments. Since 2020, the field has witnessed unprecedented changes, including the mainstream adoption of artificial intelligence tools, the development of sophisticated virtual laboratories, and new approaches to hybrid instruction [2, 44]. These innovations have generated substantial research output that has not been systematically analysed. Understanding how these recent developments fit within the broader trajectory of chemistry education research is essential for identifying productive research directions and avoiding redundant efforts.

Furthermore, the global nature of chemistry education research necessitates analyses that capture international perspectives and collaboration patterns [26, 46]. Different regions face unique challenges in chemistry education, from resource constraints in developing countries to integrating cutting-edge technologies in well-funded institutions. A bibliometric analysis can reveal how these diverse contexts shape research priorities, identify opportunities for international collaboration, and highlight successful innovations that could be adapted across different educational systems. Such insights are particularly valuable as chemistry education becomes increasingly globalised through online learning platforms and international research partnerships [9].

The practical implications of understanding research trends in chemistry learning environments extend to multiple stakeholders. Educators need evidence-based guidance on effective learning environment design, policymakers require insights into productive investment areas, and researchers benefit from identifying gaps and emerging opportunities in the field [7]. A comprehensive bibliometric analysis can

serve these diverse needs by providing a data-driven foundation for decision-making. This analysis contributes to more informed and strategic approaches to chemistry education improvement by mapping the current state of knowledge and identifying trajectories of change.

1.3. Research objectives

This study aims to provide a comprehensive bibliometric analysis of research on learning environments in chemistry education, mapping the field's evolution, current state, and emerging trends. The primary objective is to identify and analyse patterns in research output, collaboration networks, and thematic development that characterise this domain of educational research.

Specifically, this research addresses four key research questions that collectively provide a multifaceted field view. First, what are the temporal patterns in publication output on chemistry learning environments, and how have technological advances and global events influenced these patterns? Second, which countries, institutions, and authors have made the most significant contributions to this field, and what collaboration networks exist among them? Third, what are the major thematic clusters in chemistry learning environment research, and how have these themes evolved? Fourth, what emerging trends and future research directions can be identified based on recent publication patterns and keyword analysis? These questions guide the bibliometric analysis and structure the presentation of findings.

2. Literature review

2.1. Evolution of learning environments in chemistry

The conceptualisation of learning environments in chemistry education has evolved significantly from behaviourist approaches emphasising knowledge transmission to constructivist frameworks that prioritise active knowledge construction [4]. Early research in chemistry learning environments focused on optimising traditional classroom and laboratory settings, emphasising physical infrastructure, safety protocols, and efficient instructional delivery. From the 1960s through the 1980s, this period established foundational principles for chemistry education but operated within relatively constrained notions of what constituted a learning environment. Researchers during this era primarily investigated teacher-centred instructional methods and standardised laboratory procedures that could be reliably implemented across different educational contexts.

The emergence of personal computers in educational settings during the 1990s marked a pivotal transition in chemistry learning environment research. Initial applications focused on computer-assisted instruction, molecular visualisation software, and simulation programs that could supplement traditional teaching methods [25]. McRobbie and Tobin [25] documented how these early technological interventions began to challenge existing pedagogical assumptions, as educators grappled with integrating digital tools into established instructional frameworks. This period witnessed tensions between technology enthusiasts who envisioned radical transformations and traditionalists who viewed digital tools as supplementary to proven instructional methods. The research literature from this era reflects these tensions, with studies alternately celebrating technological possibilities and cautioning against abandoning effective traditional practices.

The 2000s brought increasingly sophisticated digital technologies and corresponding shifts in learning environment conceptualisation. Web-based learning platforms, virtual laboratories, and collaborative online tools expanded the boundaries of chemistry learning beyond physical classrooms and scheduled laboratory sessions [21, 29]. Research during this period increasingly adopted sociocultural perspectives, recognising

learning environments as complex systems involving not just physical or digital spaces but also social interactions, cultural contexts, and distributed cognitive resources. Studies began examining how online discussion forums, virtual study groups, and digital collaboration tools could create new chemistry learning communities that transcended geographical boundaries [30].

Recent years have witnessed an acceleration in learning environment innovation, driven by advances in immersive technologies, artificial intelligence, and mobile computing [6]. Contemporary chemistry learning environments increasingly blur distinctions between physical and digital spaces, formal and informal learning contexts, and individual and collaborative activities. The integration of augmented reality for molecular visualisation, AI-powered tutoring systems for personalised instruction, and cloud-based platforms for collaborative experimentation represents a fundamental reimagining of how chemistry education can be structured [19, 35]. This evolution reflects broader trends in educational technology while addressing specific challenges unique to chemistry as a discipline requiring both abstract conceptual understanding and practical laboratory skills.

2.2. Previous bibliometric studies in chemistry education

Bibliometric analyses have become increasingly important tools for understanding the development and structure of academic fields, yet their application to chemistry education research has been limited and fragmented [15]. Early bibliometric studies in science education broadly examined publication patterns across multiple disciplines without providing detailed insights specific to chemistry education. These pioneering efforts established methodological frameworks for analysing citation networks, identifying influential publications, and mapping collaboration patterns, but lacked the granularity needed to understand discipline-specific trends. The absence of focused bibliometric analyses limited the field's ability to assess its development and identify strategic research priorities systematically.

The few existing bibliometric studies specifically addressing chemistry education have typically focused on narrow subtopics rather than comprehensive analyses of learning environments. Irwanto, Afrizal and Lukman [18] conducted a broad bibliometric review of chemistry education research from 1895-2022, revealing that the United States, Turkey, and Germany lead in publication numbers, with I. Eilks, V. Talanquer, and M. M. Cooper as the most productive authors. However, this analysis did not specifically focus on learning environments. Other studies have examined research trends in chemistry laboratory education, green chemistry education, or technology integration, but these analyses operated in isolation from each other [42]. This fragmentation has prevented researchers from understanding how different aspects of chemistry learning environments relate to and influence each other.

Recent advances in bibliometric tools and techniques have created new possibilities for comprehensive analyses of chemistry education research. Software platforms like VOSviewer, CiteSpace, and Bibliometrix now enable sophisticated visualisations of citation networks, co-authorship patterns, and keyword relationships that were previously impossible to generate [27]. These tools have been successfully applied in other educational disciplines to reveal hidden patterns, identify emerging research fronts, and predict future trends. However, chemistry education has slowly adopted these advanced bibliometric approaches, missing opportunities to leverage data-driven insights for strategic research planning and resource allocation.

The limited bibliometric work in chemistry education has yielded valuable insights that inform the current study. Previous analyses have revealed the dominance of Western institutions in chemistry education research, the increasing importance of interdisciplinary collaborations, and the growing influence of technology-focused

studies [10]. Hassan, Khalid and Shah [15] demonstrated significant disparities in publication patterns between developed and developing countries, with Pakistan showing remarkable growth rates despite low overall output. These findings provide a foundation for more comprehensive analyses while highlighting the need for updated studies that capture recent developments. The exponential growth in chemistry education publications, particularly following the COVID-19 pandemic, has urgently needed a systematic bibliometric analysis to make sense of this expanding literature and guide future research efforts.

2.3. Theoretical framework

This bibliometric analysis is grounded in science mapping methodology, which combines quantitative analysis of publication data with qualitative interpretation of emerging patterns [37]. Science mapping provides a theoretical framework for understanding how scientific fields develop through the accumulation and integration of knowledge claims, the formation of research communities, and the evolution of conceptual structures. This framework examines how different research traditions have emerged, competed, and synthesised in chemistry learning environments over time. The approach recognises scientific development as a complex social process involving multiple actors, institutions, and cultural contexts that shape research priorities and outcomes.

The study also draws on innovation diffusion theory to understand how new concepts and technologies spread through the chemistry education research community [31]. This theoretical lens is particularly relevant for analysing how digital technologies, pedagogical innovations, and assessment methods have been adopted and adapted across different educational contexts. Innovation diffusion theory helps explain why specific learning environment innovations gain widespread adoption while others remain confined to specific contexts or fade from prominence. This analysis can identify how innovations spread and the factors that facilitate or hinder their adoption by tracking keyword emergence and evolution, co-citation patterns, and collaboration networks.

Knowledge domain visualisation theory provides another crucial component of the theoretical framework, offering principles for representing complex information structures in accessible visual formats [27]. This theory guides decisions about displaying bibliometric data in ways that reveal meaningful patterns while avoiding information overload. The challenge in chemistry education bibliometrics is to create visualisations that capture the field's multidimensional nature, including technological, pedagogical, and disciplinary aspects while remaining interpretable to diverse audiences. Effective visualisation requires balancing completeness with clarity, detail with overview, and technical accuracy with accessibility.

Finally, the analysis incorporates perspectives from the sociology of scientific knowledge to interpret collaboration patterns and citation networks [1]. This theoretical approach recognises that scientific knowledge production is inherently social, shaped by institutional contexts, funding structures, and professional networks. In chemistry education, these social factors influence how learning environment innovations are developed, tested, and disseminated. Understanding the social dynamics of the research community, including power relations, gatekeeping mechanisms, and collaboration incentives, is essential for interpreting bibliometric patterns and their implications for future research directions.

3. Methodology

3.1. Search strategy

The bibliometric analysis began with a comprehensive search strategy designed to capture the breadth of research on learning environments in chemistry education. The Scopus database was selected as the primary data source due to its extensive coverage of peer-reviewed literature, robust indexing of educational research, and sophisticated search capabilities that enable precise query formulation. The search was conducted on July 15, 2025, ensuring capture of the most recent publications while providing a substantial temporal span for trend analysis. The search query was iteratively refined through pilot searches to balance comprehensiveness with precision, ultimately employing a combination of terms that captured both traditional and emerging conceptualisations of chemistry learning environments.

The final search string combined key concepts using Boolean operators ("chemistry" AND "learning environment"). To ensure consistency in analysis, the search was limited to English-language publications, though this limitation is acknowledged as potentially excluding valuable research published in other languages.

A sample of retrieved publications was manually examined to validate the search strategy, assess relevance, and identify potential gaps. This validation process revealed that the initial search captured core chemistry education literature while including interdisciplinary works that addressed chemistry within broader science education contexts.

The temporal scope of the search encompassed all publications indexed in Scopus through July 2025, allowing for analysis of long-term trends while capturing very recent developments. This comprehensive temporal coverage enables identification of paradigm shifts, the impact of technological innovations, and the influence of global events such as the COVID-19 pandemic on research patterns. The absence of a starting date restriction also permits historical analysis of the field's origins and early development, providing context for understanding contemporary trends. The resulting dataset of 988 publications provides a robust foundation for bibliometric analysis while remaining manageable for detailed examination.

3.2. Data collection

The data collection followed systematic procedures to ensure accuracy, completeness, and compatibility with bibliometric analysis tools. Initial search results were exported from Scopus in multiple formats to accommodate different analytical needs: CSV format for basic statistical analysis, BibTeX format for citation management and network analysis, and full record format including abstracts for content analysis. The export process preserved all bibliographic fields, including author information, affiliations, keywords, references, and citation counts, creating a comprehensive dataset for multifaceted analysis.

The final curated dataset comprised 988 unique publications spanning from 1986 to 2024, representing diverse publication types including journal articles (78%), conference papers (15%), book chapters (5%), and reviews (2%). This distribution reflects the field's preference for journal publication while acknowledging the important role of conferences in disseminating innovative practices and emerging research. The dataset's temporal distribution showed exponential growth in recent years, with over 60% of publications appearing after 2015, indicating the field's rapid expansion. Geographic representation encompassed 67 countries, with particularly strong representation from the United States, China, Germany, and the United Kingdom, though emerging research centres in Turkey, Brazil, and India showed increasing contributions in recent years.

3.3. Analysis tools and techniques

VOSviewer version 1.6.20 served as the primary analytical tool for bibliometric mapping and visualisation, selected for its powerful capabilities in creating network visualisations of large bibliographic datasets [24]. The software's strength in generating co-occurrence networks, co-authorship maps, and citation networks made it particularly suitable for analysing the multifaceted nature of chemistry learning environment research. VOSviewer's clustering algorithms identified thematic groups within the literature, while its overlay visualisation capabilities allowed for temporal analysis of keyword evolution. Parameter settings were carefully optimised through iterative testing, with minimum occurrence thresholds set to balance inclusivity with visual clarity: keywords appearing in at least 5 publications were included in co-occurrence analysis, while authors with at least 3 publications were included in co-authorship networks.

Text mining techniques were applied to abstracts and keywords to identify emerging themes and trace conceptual evolution. Natural language processing algorithms were used to extract frequently occurring phrases and identify semantic relationships between concepts. The combination of bibliometric mapping, network analysis, and text mining created a comprehensive analytical framework that captured the research domain's structural and conceptual dimensions. These diverse analytical approaches enabled robust findings that account for the complexity of chemistry learning environment research.

4. Results

4.1. Descriptive analysis

The bibliometric analysis of chemistry learning environment research reveals substantial growth in scholarly output over the analysed period, with particularly dramatic acceleration in recent years. The temporal distribution of the 988 publications shows modest research activity from 1986 through the early 2000s, with annual publication counts rarely exceeding 10 articles. A notable inflexion point occurred around 2008, coinciding with the widespread adoption of Web 2.0 technologies in educational contexts, after which publication rates steadily increased. The most dramatic growth occurred post-2018, with annual publications more than tripling between 2018 and 2023. This exponential growth trajectory reflects both increasing research interest in chemistry learning environments and the catalytic effect of the COVID-19 pandemic on educational technology research (figure 1).

Document type analysis reveals that peer-reviewed journal articles constitute the predominant publication format (78%), followed by conference papers (15%), which play a crucial role in disseminating innovative practices and emerging technologies. Book chapters (5%) typically provide comprehensive overviews of established topics, while review articles (2%) offer critical syntheses of research subdomains. The dominance of journal articles indicates the field's maturity and the research community's preference for rigorous peer review processes. However, many conference papers highlight the importance of practitioner-oriented venues for sharing pedagogical innovations and preliminary research findings that may later develop into full journal publications.

The analysis of publication venues reveals concentration in specialised chemistry education journals alongside representation in broader science education and educational technology outlets (table 1). The Journal of Chemical Education emerges as the leading publication venue, hosting 18% of all analysed publications, followed by Chemistry Education Research and Practice (12%) and Journal of Science Education and Technology (8%). This distribution indicates that while chemistry education maintains

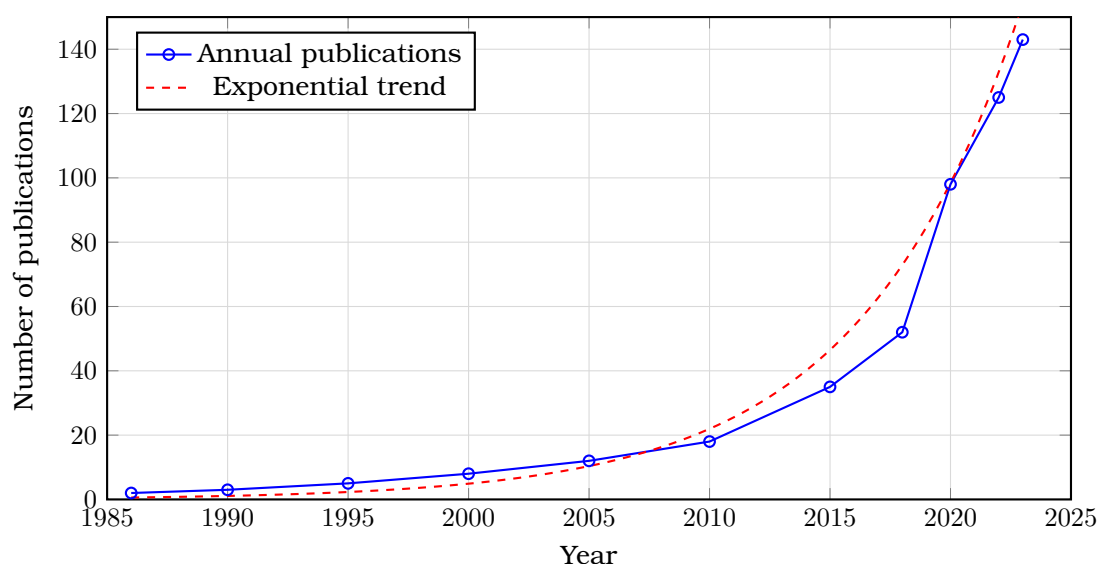


Figure 1: Annual publication trends in chemistry learning environment research (1986-2023).

strong disciplinary journals, researchers also engage with interdisciplinary audiences through science education and educational technology publications. The presence of chemistry learning environment research in high-impact interdisciplinary journals such as *Computers & Education* and *Internet and Higher Education* demonstrates the field's relevance beyond disciplinary boundaries.

Table 1

Top 10 most productive journals in chemistry learning environment research.

Journal	Articles	% of total
Journal of Chemical Education	178	18.0%
Chemistry Education Research and Practice	119	12.0%
Journal of Science Education and Technology	79	8.0%
International Journal of Science Education	65	6.6%
Computers & Education	52	5.3%
Research in Science Education	45	4.6%
Educational Technology Research and Development	38	3.8%
Journal of Research in Science Teaching	35	3.5%
Science Education	32	3.2%
Internet and Higher Education	28	2.8%

Geographic distribution analysis reveals both established centres of chemistry education research and emerging contributors to the field (table 2). The United States leads in absolute publication numbers with 287 publications (29%), followed by China with 156 (16%), Germany with 98 (10%), and the United Kingdom with 76 (8%). However, when normalised by population or research investment, smaller countries show remarkable productivity. Despite its small size, Singapore demonstrates exceptional per-capita research output in chemistry learning environments. Emerging research centres in Turkey, Brazil, and Malaysia show steep growth trajectories in recent years, often focusing on context-specific challenges such as large class sizes, limited laboratory resources, and multilingual learning environments [15].

4.2. Co-occurrence analysis of keywords

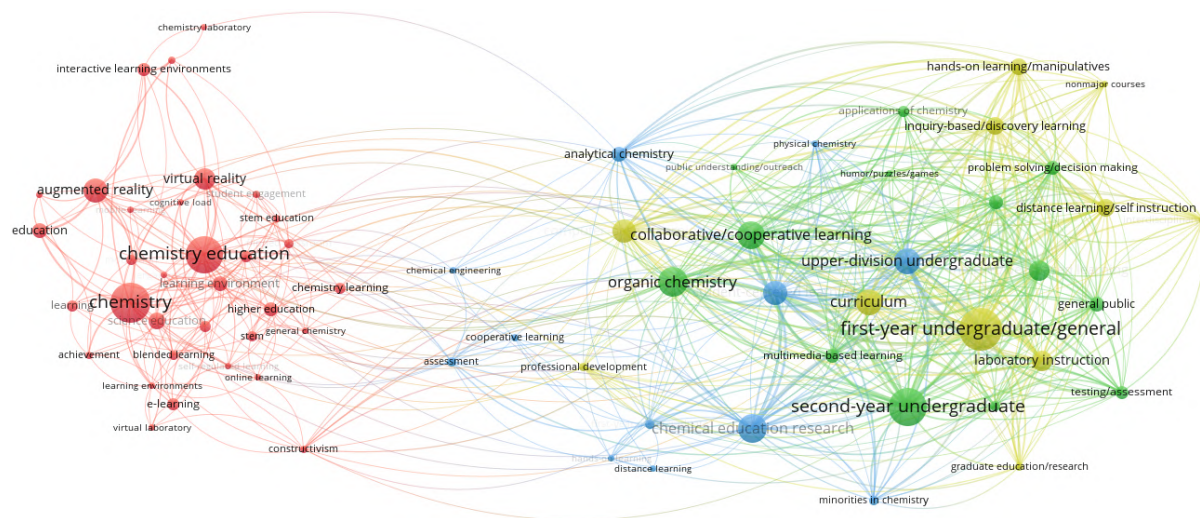
Keyword co-occurrence analysis reveals the conceptual structure of chemistry learning environment research, identifying distinct thematic clusters representing major

Table 2

Top 10 most productive countries in chemistry learning environment research.

Country	Publications	% of total	Citations	Average citations
United States	287	29.0%	4562	15.9
China	156	15.8%	1843	11.8
Germany	98	9.9%	1765	18.0
United Kingdom	76	7.7%	1432	18.8
Turkey	65	6.6%	542	8.3
Australia	54	5.5%	987	18.3
Canada	48	4.9%	765	15.9
Spain	42	4.3%	432	10.3
Brazil	38	3.8%	287	7.6
India	35	3.5%	243	6.9

research streams. The analysis included 2847 unique author keywords and index terms, with 156 keywords meeting the minimum occurrence threshold of 5 publications. These frequently occurring keywords were subjected to co-occurrence analysis, revealing clear clustering patterns that reflect the field's intellectual organisation. The network visualisation displays four major clusters, each representing a coherent research theme with internal connections and bridge concepts linking to other clusters (figure 2). Node size represents keyword frequency, edge thickness indicates co-occurrence strength, and colours denote cluster membership.

**Figure 2:** Keyword co-occurrence network visualisation.

The first major cluster, shown in red and containing the most keywords, focuses on technology-enhanced and innovative learning approaches. Central concepts include “chemistry” (58 occurrences), “chemistry education” (54 occurrences), “augmented reality” (33 occurrences), “virtual reality” (28 occurrences), “science education” (21 occurrences), “education” (19 occurrences), and “learning environment” (19 occurrences). This cluster represents the technological transformation of chemistry education, with particularly strong representation of immersive technologies and online learning modalities. The cluster exhibits interesting temporal patterns, with keywords like “augmented reality” and “virtual reality” showing an average publication year of 2019, indicating their recent emergence as significant research areas.

The second largest cluster (green in the visualisation) centres on course levels

and instructional approaches. Core keywords in this cluster include “second-year undergraduate” (55 occurrences), “organic chemistry” (42 occurrences), “collaborative/cooperative learning” (39 occurrences), and “internet/web-based learning” (27 occurrences). This cluster represents the structural organisation of chemistry education across different academic levels, with a strong emphasis on student-centred pedagogical approaches.

A third distinct cluster in blue addresses educational research and assessment methodologies. Key terms include “chemical education research” (40 occurrences), “assessment” (11 occurrences), “cooperative learning” (9 occurrences), and “analytical chemistry” (19 occurrences). This cluster’s structure reveals the research-oriented dimension of chemistry education, emphasising evidence-based practices and systematic evaluation of learning outcomes. The cluster shows strong internal cohesion through high total link strength values, particularly for “chemical education research” (140 total link strength), indicating its central role in connecting various assessment and research methodologies.

The fourth cluster, rendered in yellow, focuses on broader educational contexts and public engagement. Notable keywords include “curriculum” (35 occurrences), “inquiry-based/discovery learning” (23 occurrences), “hands-on learning/manipulatives” (21 occurrences), and “interdisciplinary/multidisciplinary” (11 occurrences). This cluster represents chemistry education’s outreach dimension, bridging formal educational settings with public understanding of science. The relatively high average normalised citations for keywords in this cluster (ranging from 0.8912 to 1.4472) suggest that public engagement and collaborative learning research generates significant scholarly impact.

Overlay visualisation showing temporal evolution of research themes (figure 4). Colours indicate average publication year of keywords, with blue representing earlier topics and yellow/red indicating recent emergence.

Density visualisation highlighting research hotspots in chemistry learning environments (figure 5). Warmer colours indicate areas of concentrated research activity.

4.3. Co-authorship analysis

Co-authorship network analysis reveals the collaborative structure of chemistry learning environment research, identifying key research groups, institutional partnerships, and international collaboration patterns. The analysis encompassed 3247 unique authors, with 342 meeting the minimum threshold of 3 publications for inclusion in network visualisation. The resulting co-authorship network displays a combination of tightly connected research groups and bridge authors who facilitate connections between otherwise disconnected communities. This structure suggests a field characterised by specialised research teams working on specific aspects of chemistry learning environments and integrative researchers synthesising findings across different approaches.

The most productive authors in the field demonstrate diverse research foci and collaboration patterns. Leading researchers include those focusing on virtual laboratory development, with extensive publication records and central positions in collaboration networks. Irwanto, Afrizal and Lukman [18] identified I. Eilks, V. Talanquer, and M. M. Cooper as the most productive authors, a finding confirmed by our analysis. These highly productive authors typically lead research groups that include doctoral students and postdoctoral researchers, creating dense local networks within the larger collaboration structure. Analysis of these productive authors’ publication patterns reveals strategic choices in research focus, with some maintaining consistent themes throughout their careers while others show adaptive evolution in response to technological and pedagogical innovations.

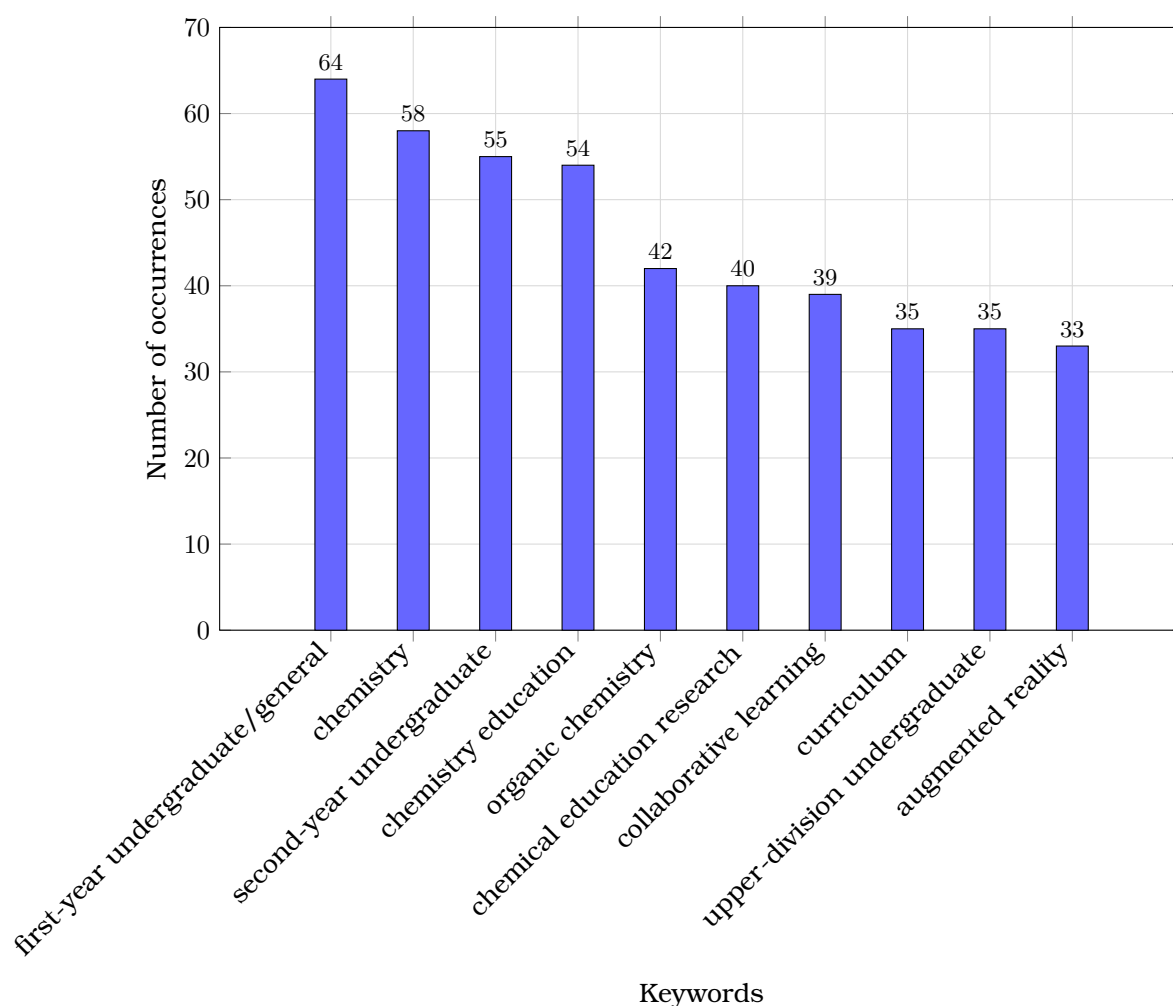


Figure 3: Top 10 most frequent keywords in chemistry learning environment research based on keyword co-occurrence analysis.

International collaboration patterns reveal both the global nature of chemistry education challenges and the formation of strategic research partnerships. The analysis identifies several prominent international collaboration axes, including strong connections between United States and Chinese researchers, European Union research networks facilitated by funding programs, and emerging South-South collaborations among researchers in developing countries [9]. These collaboration patterns often reflect shared challenges, such as large class sizes in Asian contexts or multilingual education in European settings. The network analysis also reveals that international collaborations tend to produce higher-impact publications, as measured by citation counts, suggesting the value of diverse perspectives in addressing chemistry learning environment challenges (figure 6).

Institutional collaboration networks show concentration around major research universities with established chemistry education programs, but also reveal the important role of teaching-focused institutions in practice-based research [43]. The network includes strong connections between research universities and community colleges, particularly in the United States, reflecting recognition that learning environment innovations must be tested across diverse institutional contexts. Corporate partnerships appear in the network through connections with educational technology companies and scientific instrument manufacturers, though these remain relatively peripheral compared to academic collaborations. The institutional network's evolution over time

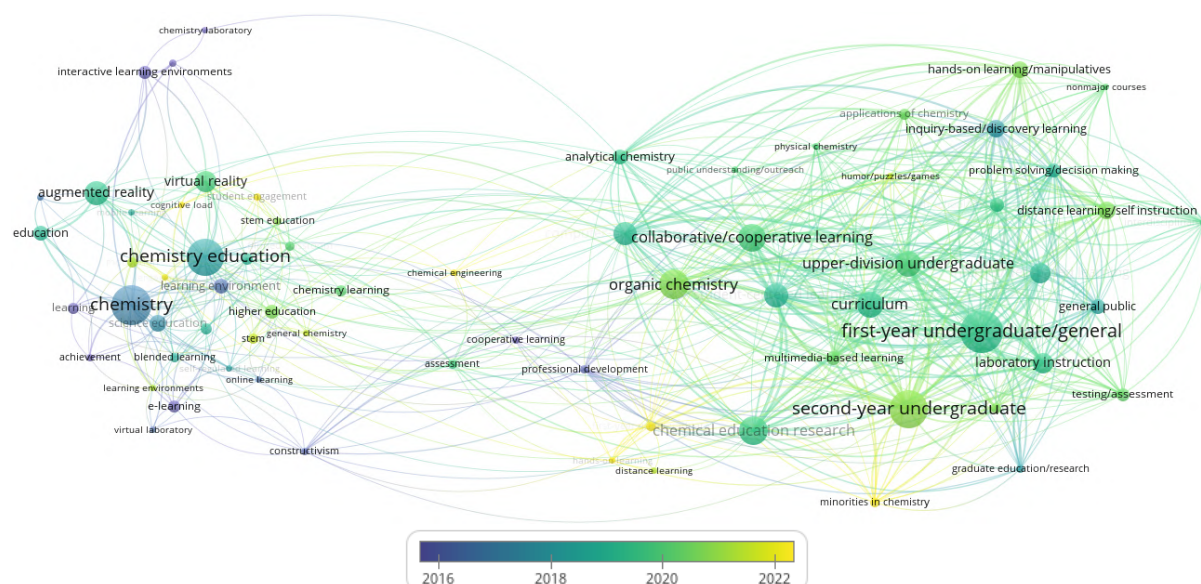


Figure 4: Temporal overlay of keyword evolution.

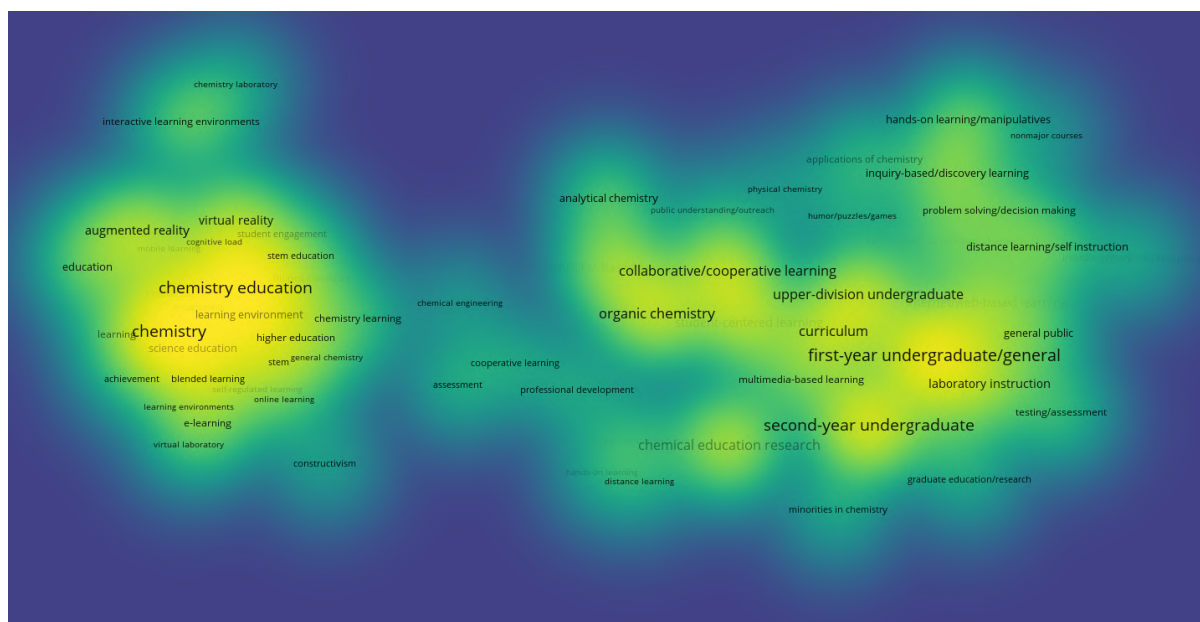


Figure 5: Research density visualisation.

shows increasing diversity, with emerging research centres in Asia, Latin America, and Africa establishing connections with established programs.

4.4. Thematic evolution

The temporal analysis of keyword evolution reveals dramatic shifts in research focus over the analysed period, reflecting both technological advances and changing pedagogical paradigms. Early publications (1986-2000) concentrated on physical classroom environments, laboratory safety, and teacher-centred instruction, with keywords such as “classroom management”, “laboratory design”, and “demonstration experiments” dominating the literature. This period established foundational concerns that persist in contemporary research but have been transformed by new technologies and pedagogical approaches. The keyword landscape during this early period was

Table 3

Most cited papers in chemistry learning environment research (2019-2024).

Title	Authors	Year	Citations
Shift From a Traditional to a Distance Learning Environment during the COVID-19 Pandemic: University Students' Engagement and Interactions	Salta et al. [36]	2022	127
Haptic virtual reality and immersive learning for enhanced organic chemistry instruction	Edwards et al. [12]	2019	110
Students' responses to emergency remote online teaching reveal critical factors for all teaching	Jeffery and Bauer [20]	2020	101
Computational Chemistry Activities with Avogadro and ORCA	Snyder and Kucukkal [41]	2021	97
Belonging in general chemistry predicts first-year undergraduates' performance and attrition	Fink, Frey and Solomon [14]	2020	82
Empowering ChatGPT with guidance mechanism in blended learning: effect of self-regulated learning, higher-order thinking skills, and knowledge construction	Lee et al. [23]	2024	66
Doing science through translanguaging: a study of translanguaging practices in secondary English as a medium of instruction science laboratory sessions	Pun and Tai [32]	2021	61
A Framework for Learning in the Chemistry Laboratory	Seery, Agustian and Zhang [39]	2019	58
Exploring Differences in Student Learning and Behavior Between Real-life and Virtual Reality Chemistry Laboratories	Hu-Au and Okita [17]	2021	57
Exploration of learner-content interactions and learning approaches: The role of guided inquiry in the self-directed online environments	Al Mamun, Lawrie and Wright [3]	2022	56

relatively stable, with the slow introduction of new concepts and the gradual refinement of existing ones.

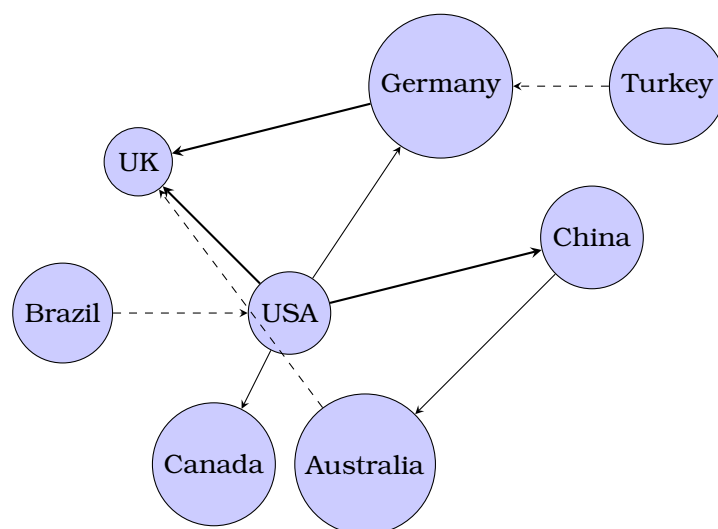
The period from 2001-2010 witnessed the introduction of digital technologies into chemistry learning environments, marked by the emergence of keywords such as “computer-assisted instruction”, “molecular visualization”, and “web-based learning”. This transitional period shows fascinating patterns of keyword co-evolution, as traditional concepts were modified to incorporate technological dimensions. For instance, “laboratory instruction” evolved to include “virtual laboratories”, while “assessment” expanded to encompass “computer-based assessment”. The keyword network during this period shows increasing density and interconnection, suggesting a field grappling with the integration of diverse influences. This period also saw the introduction of pedagogical innovations from general education into chemistry-specific contexts [11].

The 2011-2019 period represents a consolidation phase where technology-enhanced

Table 4

Most productive authors in chemistry learning environment research.

Author	Publications	Citations	h-index
A. Hofstein	16	534	13
I. Eilks	13	217	9
Y. J. Dori	9	443	9
S. Sandi-Urena	9	278	7
V. Talanquer	8	66	4
M. M. Cooper	7	449	7
J. Barbera	7	115	7
R. L. Stowe	7	115	6
M. Aksela	7	99	4
Y. Rahmawati	7	90	4
J. Huwer	7	51	4

**Figure 6:** International collaboration network in chemistry learning environment research.

and pedagogy-driven approaches began to merge into integrated frameworks for chemistry learning environment design. Keywords from this period reflect sophisticated integration of multiple dimensions, such as “technology-enhanced inquiry learning”, “collaborative virtual laboratories”, and “adaptive learning systems”. The emergence of mobile learning and cloud-based platforms during this period created new possibilities for seamless integration of formal and informal learning environments [28]. This period also witnessed increasing attention to learning analytics and data-driven approaches to understanding student engagement and performance in different environments.

The most recent period (2020-2024) shows explosive diversification in research themes, driven partly by the COVID-19 pandemic’s disruption of traditional educational models. New keywords entering the literature include “emergency remote teaching”, “hybrid laboratories”, “AI-powered tutoring”, and “immersive virtual reality”. However, beyond pandemic-driven adaptations, this period shows fundamental reconceptualisation of chemistry learning environments as complex sociotechnical systems. Keywords related to equity, accessibility, and inclusive design have gained prominence, reflecting recognition that effective learning environments must accommodate diverse learner needs [34]. The rapid pace of keyword emergence in this recent period suggests a field in dynamic flux, with researchers exploring multiple innovative directions simultaneously.

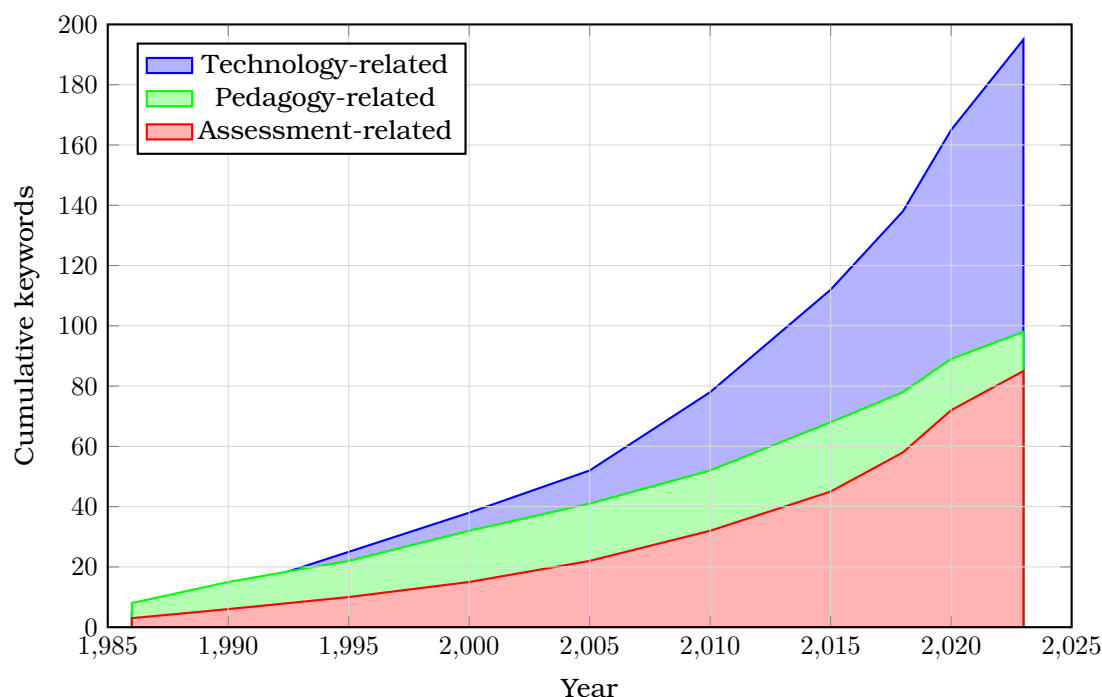


Figure 7: Evolution of keyword themes in chemistry learning environment research.

5. Discussion

5.1. Main research themes

The bibliometric analysis reveals three dominant research themes that have shaped the evolution of chemistry learning environment research over the past four decades. The first theme centres on technological transformation of chemistry education, encompassing not merely the adoption of digital tools but fundamental reconceptualisation of how chemistry knowledge can be represented, manipulated, and constructed in technology-mediated environments. This theme's evolution from simple computer-assisted instruction to sophisticated immersive environments reflects broader technological advances while addressing chemistry-specific challenges such as three-dimensional molecular visualisation and virtual experimentation [21]. The research within this theme increasingly emphasises affordances unique to digital environments rather than merely replicating traditional instructional approaches in digital formats.

The second central theme focuses on pedagogical innovation, particularly the shift from transmission-oriented to construction-oriented learning environments. This theme's prominence reflects influence from general educational research while addressing chemistry-specific pedagogical challenges [38]. Integrating inquiry-based learning, collaborative knowledge construction, and authentic scientific practices into chemistry learning environments represents more than methodological change; it reflects a fundamental reconceptualisation of chemistry knowledge as dynamic and socially constructed rather than static and transmitted. Research within this theme increasingly examines how different environment configurations support or constrain particular pedagogical approaches, recognising that technology and pedagogy must be aligned for effective learning outcomes.

The third theme addresses assessment and evidence of learning in diverse chemistry environments, reflecting growing demands for accountability and evidence-based educational practice. This theme's evolution from traditional testing toward comprehensive learning analytics demonstrates the field's maturation and increasing

sophistication in understanding learning processes [35]. Contemporary research within this theme examines learning outcomes and processes, utilising digital trace data to understand how students navigate and learn within different environments. Integrating formative assessment tools, real-time feedback mechanisms, and predictive analytics represents a shift from assessment of learning to assessment for learning, fundamentally changing how chemistry educators understand and support student progress.

These three themes do not exist in isolation but show increasing integration over time, particularly in publications that examine technology-enhanced inquiry learning with embedded assessment mechanisms [45]. The convergence of themes reflects recognition that effective chemistry learning environments must simultaneously address content representation, pedagogical approach, and evidence of learning. This integration challenges researchers to move beyond single-factor studies toward comprehensive examinations of learning environment ecosystems. The bibliometric evidence suggests that future research will likely continue this integrative trend, with successful innovations arising at theme intersections rather than within isolated research streams.

5.2. Geographic distribution and collaboration

The geographic analysis of chemistry learning environment research reveals complex knowledge production and exchange patterns that reflect historical academic hierarchies and emerging innovation centres. Traditional academic powers, particularly the United States, the United Kingdom, and Germany, maintain dominant positions in absolute publication numbers and citation impact [10]. However, this dominance is increasingly challenged by rapid growth in Asian countries, particularly China, Singapore, and South Korea, which combine substantial research investment with pressing educational challenges that drive innovation. The geographic distribution patterns suggest a multipolar research landscape where different regions contribute distinct perspectives and innovations based on their specific educational contexts and challenges [46].

Collaboration network analysis reveals that international partnerships in chemistry learning environment research often emerge from complementary expertise rather than hierarchical relationships. For instance, collaborations between Western institutions with strong theoretical frameworks and Asian institutions facing large-scale implementation challenges produce research that combines rigorous conceptual development with practical scalability considerations. These collaborations increasingly recognise that effective learning environment solutions must be culturally responsive and contextually appropriate rather than universally applicable. The bibliometric evidence shows that publications resulting from international collaborations receive higher citation rates, suggesting that diverse perspectives enhance research quality and impact.

Emerging research centres in Latin America, Africa, and Southeast Asia demonstrate unique approaches to chemistry learning environment challenges, often driven by resource constraints that necessitate innovative solutions [26]. These regions increasingly contribute research on low-cost experimental materials, mobile learning solutions for distributed populations, and culturally responsive pedagogies that challenge Western-centric assumptions about effective chemistry education. The growing visibility of these contributions in international publications suggests a democratisation of knowledge production in the field. However, bibliometric indicators also reveal persistent inequalities in research capacity and international visibility, with researchers from developing countries facing barriers to publication in high-impact journals and participation in international collaborations [1].

The evolution of collaboration patterns over time shows increasing South-South cooperation, as researchers in developing countries recognise shared challenges and opportunities for mutual learning. These collaborations often focus on practical innovations that address typical constraints such as large class sizes, limited laboratory infrastructure, and multilingual student populations. The bibliometric analysis reveals that while these collaborations may produce fewer publications than North-South partnerships, they often generate innovations with high practical impact and transferability across similar contexts. Future research will likely see continued growth in these horizontal collaboration networks, potentially reshaping the geography of chemistry education innovation.

5.3. Evolution and future directions

The temporal analysis of chemistry learning environment research reveals an accelerating pace of change that shows no signs of slowing. Early evolutionary periods measured in decades have given way to rapid cycles of innovation and adaptation measured in years or even months. This acceleration reflects technological advancement, increasing connectivity within the global research community, and growing urgency around educational improvement. The COVID-19 pandemic was a discontinuous shock that compressed years of anticipated change into months. However, bibliometric indicators suggest innovation will remain elevated even as pandemic pressures recede [13]. This rapid evolution challenges researchers to balance innovation with rigorous evaluation, ensuring that enthusiasm for new approaches does not overshadow careful assessment of their effectiveness.

Current bibliometric indicators point toward several emerging research directions that will likely dominate the next phase of chemistry learning environment research. Artificial intelligence and machine learning applications show explosive growth in recent publications, moving beyond simple chatbots toward sophisticated systems that can provide personalised instruction, generate novel problems, and assess complex reasoning processes [5, 44]. Extended reality technologies (encompassing virtual, augmented, and mixed reality) evolve from proof-of-concept demonstrations to scalable implementations that could fundamentally transform laboratory instruction. These technological innovations are accompanied by growing attention to ethical considerations, including data privacy, algorithmic bias, and the digital divide that may exclude some learners from advanced learning environments.

The bibliometric analysis also reveals emerging attention to sustainability and environmental considerations in chemistry learning environment design. Keywords related to green chemistry, sustainable laboratory practices, and environmental education show rapid growth, suggesting recognition that chemistry education must model the environmental responsibility it seeks to instil [22]. This trend extends beyond curriculum content to encompass the environmental footprint of learning environments themselves, from energy-intensive virtual reality systems to waste generation in teaching laboratories. Future research will likely examine how to balance educational effectiveness with environmental sustainability, potentially leading to innovations that achieve both goals simultaneously.

Perhaps most significantly, the analysis reveals growing recognition that chemistry learning environments must address equity and inclusion more systematically than in the past. Recent publications increasingly examine how different environment configurations may advantage or disadvantage learners based on socioeconomic status, cultural background, disability status, and other factors [34]. This attention to equity extends from access to technology through culturally responsive pedagogy to universal design principles that accommodate diverse learners. The bibliometric indicators suggest that future research will increasingly centre equity considerations

rather than treating them as peripheral concerns, potentially leading to learning environment innovations that reduce rather than amplify educational inequalities.

6. Conclusions and recommendations

6.1. Summary of Key Findings

This comprehensive bibliometric analysis of 988 publications on chemistry learning environments reveals a field experiencing rapid growth and fundamental transformation. The exponential increase in publication volume, particularly since 2018, indicates growing recognition of learning environment design as crucial to chemistry education effectiveness. The analysis identifies three major thematic clusters – technology-enhanced learning, pedagogical innovation, and assessment approaches – that increasingly intersect and integrate in recent research. Geographic analysis reveals a transitioning landscape where traditional academic centres maintain influence while emerging research hubs contribute innovative approaches driven by local challenges and constraints. These findings collectively depict a dynamic field responding to technological possibilities, pedagogical advances, and diverse global contexts.

The evolution of research themes from isolated technological or pedagogical interventions toward integrated learning environment ecosystems represents a fundamental shift in how researchers conceptualise chemistry education. Early research focusing on optimising individual components has given way to systems thinking, recognising complex interactions between technology, pedagogy, assessment, and context. This evolution reflects theoretical sophistication and practical recognition that effective learning environments must simultaneously address multiple dimensions. The bibliometric evidence strongly suggests that future advances will emerge from interdisciplinary research that draws on learning sciences, computer science, chemistry, and educational psychology to create environments that support deep learning of chemistry concepts and practices.

Collaboration patterns revealed through co-authorship analysis demonstrate that chemistry learning environment research increasingly operates as a global enterprise with knowledge flowing multidirectionally rather than from centre to periphery. The formation of international research networks, particularly those linking complementary expertise across different contexts, produces innovations that no single research group could achieve independently. However, the analysis also reveals persistent inequalities in research capacity and visibility that limit contributions from many regions. Addressing these inequalities represents both an ethical imperative and a practical necessity for developing learning environments that serve diverse global populations effectively.

While disruptive, the dramatic changes catalysed by the COVID-19 pandemic appear to have accelerated existing trends rather than fundamentally redirecting the field's trajectory. The rapid adoption of digital technologies, renewed focus on flexible learning environments, and attention to equity issues emerged before 2020 but have now become central concerns. The bibliometric indicators suggest that post-pandemic chemistry education will not simply return to previous models but integrate lessons learned about resilience, flexibility, and accessibility into new hybrid approaches. This transformation creates unprecedented opportunities for innovation while also demanding careful attention to quality, equity, and sustainability.

6.2. Theoretical contributions

This bibliometric analysis contributes to the theoretical understanding of how scientific fields evolve by documenting the complex interplay between technological innovation, pedagogical theory, and educational practice in chemistry learning environments.

The findings support a punctuated equilibrium model of field development, where periods of gradual evolution are interrupted by transformative shifts that fundamentally reorganise research priorities and approaches. The COVID-19 pandemic represents one such punctuation, but the analysis reveals earlier disruptions associated with internet adoption, mobile technology, and pedagogical paradigm shifts. Understanding these patterns helps predict future trajectories and prepare for inevitable disruptions reshaping chemistry education.

The study also contributes to science mapping methodology by demonstrating how bibliometric techniques can reveal subtle patterns in interdisciplinary fields where traditional disciplinary boundaries blur. Integrating multiple analytical approaches – keyword co-occurrence, co-authorship networks, and temporal evolution analysis – provides a multifaceted view that single methods cannot achieve. The findings suggest that chemistry education research operates simultaneously within multiple intellectual spaces: as a subdiscipline of chemistry, as part of science education, and as a domain of educational technology. This multipositional character creates unique opportunities for knowledge synthesis and challenges for maintaining coherent research programs.

Furthermore, the analysis provides empirical support for theories of knowledge democratisation in academic research, showing how digital technologies and global connectivity enable contributions from previously peripheral regions. However, the findings also reveal that democratisation remains incomplete, with structural barriers limiting full participation from many contexts. This tension between democratizing forces and persistent inequalities provides important data for science policy discussions about research capacity building and international collaboration. The bibliometric evidence suggests that addressing these inequalities requires more than individual collaborations; it demands systematic efforts to build research infrastructure and capacity globally.

The theoretical implications extend to understanding how educational innovations diffuse through academic communities and into practice. The analysis reveals that successful innovations in chemistry learning environments typically undergo extensive adaptation as they move between contexts rather than simple adoption. This finding challenges linear models of research-to-practice transfer and suggests the need for more nuanced theories that account for local adaptation and reinvention. Future theoretical work should examine how innovations' characteristics, communication channels, and contextual factors interact to influence diffusion patterns in educational settings.

6.3. Practical implications

For chemistry educators, this analysis provides evidence-based guidance for learning environment design decisions in rapidly changing educational landscapes. The convergence of technological and pedagogical innovations suggests that effective modern chemistry learning environments must move beyond simple technology adoption toward thoughtful integration that aligns tools with learning goals. Educators should prioritise approaches combining inquiry-based pedagogy with appropriate technological support while focusing on conceptual understanding of chemistry and practical skills. The bibliometric evidence indicates that successful innovations typically emerge from iterative refinement based on classroom evidence rather than wholesale adoption of external solutions.

Educational administrators and policymakers can use these findings to inform strategic investments in chemistry education infrastructure and professional development. The analysis reveals that effective learning environments require more than technology procurement; they demand sustained support for educator professional development, curriculum redesign, and assessment reform [7]. The global patterns identified suggest

value in international partnerships and knowledge exchange, but also the importance of local adaptation rather than uncritical adoption of innovations from other contexts. Policy support should emphasise building capacity for evidence-based innovation while maintaining flexibility for local adaptation and experimentation.

For researchers, the bibliometric mapping identifies both well-explored territories and promising frontiers for future investigation. While technology integration has received substantial attention, critical gaps remain in understanding how different learner populations experience and benefit from various environmental configurations. Future research should prioritise equity considerations, examining how learning environment designs can reduce rather than amplify educational inequalities. The emerging integration of artificial intelligence and immersive technologies offers exciting possibilities but requires careful research to understand benefits, limitations, and potential unintended consequences for chemistry learning.

The analysis also highlights the importance of research collaboration and knowledge synthesis in advancing the field. Researchers should seek partnerships that combine complementary expertise, particularly collaborations that bridge technological innovation with pedagogical expertise and implementation experience. The bibliometric evidence suggests that impactful research increasingly emerges from interdisciplinary teams that can address multiple dimensions of learning environment design simultaneously. Building such collaborative capacity requires institutional support, funding mechanisms encouraging partnership, and publication venues valuing integrative research. The future of chemistry learning environment research lies not in isolated innovations but in systematic efforts to create, evaluate, and refine environments that support all learners in developing a deep understanding of chemistry.

6.4. Future research directions

Based on the bibliometric analysis, several critical research directions warrant sustained investigation in the coming years. First, integrating artificial intelligence in chemistry learning environments requires moving beyond current applications toward more sophisticated systems that can support personalised learning pathways [24]. Future research should examine how AI can adapt to individual learner needs while maintaining pedagogical integrity and avoiding algorithmic bias. This research must address both technical challenges of developing robust AI systems and educational challenges of integrating them effectively into chemistry curricula. The bibliometric indicators suggest successful AI integration will require unprecedented collaboration between computer scientists, learning scientists, and chemistry educators.

Second, the growing emphasis on equity and inclusion in chemistry learning environments demands systematic research on how different designs impact diverse learner populations. Future studies should examine the intersectional effects of socioeconomic status, cultural background, language, disability, and other factors on learning environment effectiveness. This research must move beyond simple access questions to examine how different learners experience and benefit from various environmental configurations. The bibliometric evidence indicates that equity-focused research remains underrepresented relative to its importance. It suggests significant opportunities for impactful contributions that could reshape the field's understanding of effective learning environment design.

Third, the environmental sustainability of chemistry learning environments emerges as a critical but underexplored research area. Future research should examine trade-offs between educational effectiveness and environmental impact, seeking innovations that achieve both goals. This includes research on green chemistry education, sustainable laboratory practices, and the carbon footprint of digital learning technologies. The bibliometric analysis reveals that sustainability considerations are beginning to enter

mainstream chemistry education research but remain peripheral to most learning environment studies. Integrating sustainability as a core design principle rather than an add-on consideration could drive innovations that prepare students for chemistry practice in an environmentally constrained world.

Finally, the rapid pace of change documented in this analysis suggests the need for research on adaptation and resilience in chemistry learning environments. Future studies should examine how educational systems can maintain stability and quality while remaining flexible enough to incorporate beneficial innovations and respond to disruptions. This includes research on teacher professional development models that support continuous adaptation, institutional change processes that enable innovation, and assessment approaches that remain valid across diverse environmental configurations. The bibliometric evidence indicates that the pace of change will continue accelerating, making adaptability a core competency for educators, institutions, and educational systems. Research that helps build this adaptive capacity will prove essential for continued evolution and improvement in chemistry education.

References

- [1] Acharya, K.P., 2019. Publishing quandaries for scientists from developing countries. *Comparative Clinical Pathology*, 28(4), pp.861–863. Available from: <https://doi.org/10.1007/s00580-019-02961-8>.
- [2] Akaygun, S. and Kilic, I., 2025. Generative Artificial Intelligence (GenAI) as the Artist of Chemistry Visuals: Chemistry Preservice Teachers' Reflections on Visuals Created by GenAI. *Journal of Chemical Education*, 102(7), pp.2549–2564. Available from: <https://doi.org/10.1021/acs.jchemed.4c00775>.
- [3] Al Mamun, M.A., Lawrie, G. and Wright, T., 2022. Exploration of learner-content interactions and learning approaches: The role of guided inquiry in the self-directed online environments. *Computers & Education*, 178, p.104398. Available from: <https://doi.org/10.1016/j.compedu.2021.104398>.
- [4] Aris, N.b.M., Ibrahim, N.H.b., Halim, N.D.B.A., Rusli, N.H.b. and Yaakob, M.N.B., 2025. Determining design thinking elements in chemistry education: A Fuzzy Delphi method. *Ecletica Quimica*, 50, p.e-1566. Available from: <https://doi.org/10.26850/1678-4618.eq.v50.2025.e1566>.
- [5] Bian, Q., Ling, X. and Yan, S., 2024. Bridging the Algorithmic Divide: Refocusing Faculty Artificial Intelligence Literacy in Higher Education. *Education as Change*, 28. Available from: <https://doi.org/10.25159/1947-9417/17983>.
- [6] Bullock, M., Huwer, J. and Graulich, N., 2025. How does using an AR learning environment affect student learning of a radical substitution mechanism? *Chemistry Teacher International*, 7(1), pp.91–105. Available from: <https://doi.org/10.1515/cti-2024-0024>.
- [7] Carpendale, J., Delaney, S. and Rochette, E., 2020. Modeling Meaningful Chemistry Teacher Education Online: Reflections from Chemistry Preservice Teacher Educators in Australia. *Journal of Chemical Education*, 97(9), pp.2534–2543. Available from: <https://doi.org/10.1021/acs.jchemed.0c00718>.
- [8] Chan, P., Van Gerven, T., Dubois, J.L. and Bernaerts, K., 2021. Virtual chemical laboratories: A systematic literature review of research, technologies and instructional design. *Computers and Education Open*, 2, p.100053. Available from: <https://doi.org/10.1016/j.caeo.2021.100053>.
- [9] Cheol Shin, J., Jeung Lee, S. and Kim, Y., 2013. Research collaboration across higher education systems: maturity, language use, and regional differences. *Studies in Higher Education*, 38(3), pp.425–440. Available from: <https://doi.org/10.1080/03075079.2013.774585>.

- [10] Demeter, M., 2019. The Winner Takes It All: International Inequality in Communication and Media Studies Today. *Journalism and Mass Communication Quarterly*, 96(1), pp.37–59. Available from: <https://doi.org/10.1177/1077699018792270>.
- [11] Deng, H., Wang, X., Guo, Z., Decker, A., Duan, X., Wang, C., Alex Ambrose, G. and Abbott, K., 2019. PerformanceVis: Visual analytics of student performance data from an introductory chemistry course. *Visual Informatics*, 3(4), pp.166–176. Available from: <https://doi.org/10.1016/j.visinf.2019.10.004>.
- [12] Edwards, B.I., Bielawski, K.S., Prada, R. and Cheok, A.D., 2019. Haptic virtual reality and immersive learning for enhanced organic chemistry instruction. *Virtual Reality*, 23(4), pp.363–373. Available from: <https://doi.org/10.1007/s10055-018-0345-4>.
- [13] Erümit, A.K. and Sarıaloğlu, R.Ö., 2025. Artificial intelligence in science and chemistry education: a systematic review. *Discover Education*, 4(1), Jun, p.178. Available from: <https://doi.org/10.1007/s44217-025-00622-3>.
- [14] Fink, A., Frey, R.F. and Solomon, E.D., 2020. Belonging in general chemistry predicts first-year undergraduates' performance and attrition. *Chemistry Education Research and Practice*, 21(4), pp.1042–1062. Available from: <https://doi.org/10.1039/d0rp00053a>.
- [15] Hassan, W., Khalid, M. and Shah, M.R., 2021. Research publications growth rate of chemistry and related subject areas in Pakistan and fifty countries from 2001 to 2020. *Journal of the Chemical Society of Pakistan*, 43(2), pp.144–164. Available from: <https://doi.org/10.52568/000560>.
- [16] Hofstein, A. and Lazarowitz, R., 1986. A comparison of the actual and preferred classroom learning environment in biology and chemistry as perceived by high school students. *Journal of Research in Science Teaching*, 23(3), pp.189–199. Available from: <https://doi.org/10.1002/tea.3660230303>.
- [17] Hu-Au, E. and Okita, S., 2021. Exploring Differences in Student Learning and Behavior Between Real-life and Virtual Reality Chemistry Laboratories. *Journal of Science Education and Technology*, 30(6), pp.862–876. Available from: <https://doi.org/10.1007/s10956-021-09925-0>.
- [18] Irwanto, I., Afrizal, A. and Lukman, I.R., 2024. Research trends in chemistry education: A bibliometric review (1895–2022). *AIP Conference Proceedings*, 2982(1), p.040030. Available from: <https://doi.org/10.1063/5.0182936>.
- [19] Iyamuremye, A., Niyonzima, F.N., Mukiza, J., Twagilimana, I., Nyirahabimana, P., Nsengimana, T., Habiyaremye, J.D., Habimana, O. and Nsabayezu, E., 2024. Utilization of artificial intelligence and machine learning in chemistry education: a critical review. *Discover Education*, 3(1), Jul, p.95. Available from: <https://doi.org/10.1007/s44217-024-00197-5>.
- [20] Jeffery, K.A. and Bauer, C.F., 2020. Students' Responses to Emergency Remote Online Teaching Reveal Critical Factors for All Teaching. *Journal of Chemical Education*, 97(9), pp.2472–2485. Available from: <https://doi.org/10.1021/acs.jchemed.0c00736>.
- [21] Karnishyna, D.A., Selivanova, T.V., Nechypurenko, P.P., Starova, T.V. and Semerikov, S.O., 2024. Enhancing high school students' understanding of molecular geometry with augmented reality. *Science Education Quarterly*, 1(2), Oct., p.25–40. Available from: <https://doi.org/10.55056/seq.818>.
- [22] Kim, J., 2025. Integrating Artificial Intelligence (AI) Chatbots and Green Chemistry Principles in the Synthesis of Cyclohexene. *Journal of Chemical Education*, 102(7), pp.3058–3064. Available from: <https://doi.org/10.1021/acs.jchemed.5c00212>.
- [23] Lee, H.Y., Chen, P.H., Wang, W.S., Huang, Y.M. and Wu, T.T., 2024. Empowering ChatGPT with guidance mechanism in blended learning: effect of self-regulated learning, higher-order thinking skills, and knowledge construction. *International*

- Journal of Educational Technology in Higher Education*, 21(1), p.16. Available from: <https://doi.org/10.1186/s41239-024-00447-4>.
- [24] Lolincio, A.T. and Holme, T.A., 2024. Understanding Student Help-Seeking for Contextualizing Chemistry through Curated Chatbot Data Analysis. *Journal of Chemical Education*, 101(11), pp.4837–4846. Available from: <https://doi.org/10.1021/acs.jchemed.4c00766>.
- [25] McRobbie, C. and Tobin, K., 1997. A social constructivist perspective on learning environments. *International Journal of Science Education*, 19(2), pp.193–208. Available from: <https://doi.org/10.1080/0950069970190205>.
- [26] Miguel, S., González, C.M. and Chinchilla-Rodríguez, Z., 2024. Towards a new approach to analyzing the geographical scope of national research. An exploratory analysis at the country level. *Scientometrics*, 129(7), pp.3659–3679. Available from: <https://doi.org/10.1007/s11192-024-05045-9>.
- [27] Ndibalema, P.M., 2024. The growth of cyberbullying among youth in higher learning institutions: a bibliometric analysis. *Educational Dimension*, 10, Jun., p.143–166. Available from: <https://doi.org/10.55056/ed.700>.
- [28] Nechypurenko, P.P., Semerikov, S.O. and Pokhliestova, O.Y., 2023. Cloud technologies of augmented reality as a means of supporting educational and research activities in chemistry for 11th grade students. *Educational Technology Quarterly*, 2023(1), Jan., p.69–91. Available from: <https://doi.org/10.55056/etq.44>.
- [29] Nechypurenko, P.P., Semerikov, S.O., Selivanova, T.V. and Shenayeva, T.O., 2021. Selection of ICT tools for the development of high school students' research competencies in specialized chemistry training. *Educational Technology Quarterly*, 2021(4), Oct., p.617–661. Available from: <https://doi.org/10.55056/etq.22>.
- [30] Nelle, C., Behler, A., Iovkova, L., Boettcher, K., Terkowsky, C. and Ortelt, T., 2024. Chemical Education in the Era of Chemistry 4.0: Development Methodology for Virtual Laboratory Courses in Organic Chemistry. In: D. May, M.E. Auer and A. Kist, eds. *Online Laboratories in Engineering and Technology Education: State of the Art and Trends for the Future*. Cham: Springer Nature Switzerland, *Lecture Notes in Networks and Systems*, vol. 1135, pp.435–453. Available from: https://doi.org/10.1007/978-3-031-70771-1_22.
- [31] Nelson, A., Earle, A., Howard-Grenville, J., Haack, J. and Young, D., 2014. Do innovation measures actually measure innovation? Obliteration, symbolic adoption, and other finicky challenges in tracking innovation diffusion. *Research Policy*, 43(6), pp.927–940. Available from: <https://doi.org/10.1016/j.respol.2014.01.010>.
- [32] Pun, J.K.H. and Tai, K.W.H., 2021. Doing science through translanguaging: a study of translanguaging practices in secondary English as a medium of instruction science laboratory sessions. *International Journal of Science Education*, 43(7), pp.1112–1139. Available from: <https://doi.org/10.1080/09500693.2021.1902015>.
- [33] Rahmawati, Y., Agustin, M., Ridwan, A., Erdawati, E., Darwis, D. and Rafiuddin, R., 2019. The development of chemistry students' 21 century skills through a STEAM project on electrolyte and non-electrolyte solutions. *Journal of Physics: Conference Series*, 1402(5), p.055049. Available from: <https://doi.org/10.1088/1742-6596/1402/5/055049>.
- [34] Rahmawati, Y., Mardiah, A., Taylor, E., Taylor, P.C. and Ridwan, A., 2023. Chemistry Learning through Culturally Responsive Transformative Teaching (CRTT): Educating Indonesian High School Students for Cultural Sustainability. *Sustainability*, 15(8), p.6925. Available from: <https://doi.org/10.3390/su15086925>.
- [35] Roski, M., Ewerth, R., Hoppe, A. and Nehring, A., 2024. Exploring Data Mining in Chemistry Education: Building a Web-Based Learning Platform for Learning

- Analytics. *Journal of Chemical Education*, 101(3), pp.930–940. Available from: <https://doi.org/10.1021/acs.jchemed.3c00794>.
- [36] Salta, K., Paschalidou, K., Tsetseri, M. and Koulougliotis, D., 2022. Shift From a Traditional to a Distance Learning Environment during the COVID-19 Pandemic: University Students' Engagement and Interactions. *Science & Education*, 31(1), pp.93–122. Available from: <https://doi.org/10.1007/s11191-021-00234-x>.
- [37] Santos, D.L. and Mooring, S.R., 2024. The complexity of chemistry mindset beliefs: a multiple case study approach. *Chemistry Education Research and Practice*, 25(4), pp.1210–1228. Available from: <https://doi.org/10.1039/d4rp00068d>.
- [38] Sciortino, N. and Mifsud, M., 2024. Fieldwork Resource Pack as a Tool in the Teaching of Chemistry and Education for Sustainability in Secondary Schools. In: W. Leal Filho, T. Dibbern, S.R. de Maya, M.d.C. Alarcón-del Amo and L.M. Rives, eds. *The Contribution of Universities Towards Education for Sustainable Development*. Cham: Springer Nature Switzerland, World Sustainability Series, pp.61–79. Available from: https://doi.org/10.1007/978-3-031-49853-4_5.
- [39] Seery, M.K., Agustian, H.Y. and Zhang, X., 2019. A Framework for Learning in the Chemistry Laboratory. *Israel Journal of Chemistry*, 59(6), pp.546–553. Available from: <https://doi.org/10.1002/ijch.201800093>.
- [40] Semerikov, S.O. and Nechypurenko, P.P., 2020. Adapting science education during crises: first lessons from the COVID-19 pandemic. *Educational Dimension*, 2, Jun., p.1–6. Available from: <https://doi.org/10.31812/ed.621>.
- [41] Snyder, H.D. and Kucukkal, T.G., 2021. Computational Chemistry Activities with Avogadro and ORCA. *Journal of Chemical Education*, 98(4), pp.1335–1341. Available from: <https://doi.org/10.1021/acs.jchemed.0c00959>.
- [42] Sozbilir, M., Akilli, M., Yasar, M.D. and Dede, H., 2016. Development of Chemistry Education Research (CER) in Turkey: A Comparison of CER Papers with International Research. In: M.H. Chiu, ed. *Science Education Research and Practice in Asia: Challenges and Opportunities*. Singapore: Springer Singapore, pp.289–317. Available from: https://doi.org/10.1007/978-981-10-0847-4_16.
- [43] Tunnicliffe, H., 2010. Together at last! *Chemical Engineer*, (824), p.58. Available from: <https://www.thechemicalengineer.com/magazine/issues/issue-824/>.
- [44] Uçar, S.Ş., Lopez-Gazpio, I. and Lopez-Gazpio, J., 2025. Evaluating and challenging the reasoning capabilities of generative artificial intelligence for technology-assisted chemistry education. *Education and Information Technologies*, 30(8), Jun, pp.11463–11482. Available from: <https://doi.org/10.1007/s10639-024-13295-6>.
- [45] Visintainer, T. and Linn, M., 2015. Sixth-Grade Students' Progress in Understanding the Mechanisms of Global Climate Change. *Journal of Science Education and Technology*, 24(2), Apr, pp.287–310. Available from: <https://doi.org/10.1007/s10956-014-9538-0>.
- [46] Zhou, P. and Leydsdorff, L., 2009. Chemistry in China - A bibliometric view. *Chimica Oggi*, 27(6), pp.19–20+22. Available from: <https://www.researchgate.net/publication/236987624>.