Vol. 9, No. 4, 2024, pp. 72-89
DOI: https://doi.org/10.29210/027215jpgi0005

Contents lists available at Journal IICET

JPGI (Jurnal Penelitian Guru Indonesia)
ISSN: 2541-3163(Print) ISSN: 2541-3317 (Electronic)

Journal homepage: https://jurnal.iicet.org/index.php/jpgi

Teaching strategies and pedagogy in chemistry education and their neuro-pedagogical frontier: a scopus-based bibliometric mapping (2019–2023)

Sofiyanita Sofiyanita*), Mainar Fitri
Universitas Islam Negeri Sultan Syarif Kasim, Pekanbaru, Indonesia

Article Info

Article history:

Received Aug 12th, 2024
Revised Nov 20th, 2024
Accepted Dec 26th, 2024

Keyword:

Bibliometric analysis
Chemical education research
Chemistry education
Pedagogy
Teaching strategies

ABSTRACT

Research on chemistry teaching has expanded rapidly, yet its intellectual structure remains difficult to understand through narrative reading alone. This study maps the development, thematic structure, research networks, and emerging directions of chemistry education research focusing on teaching strategies, methods, approaches, and pedagogy. A corpus of 241 journal articles was retrieved from Scopus using a topic query combining chemistry, education, and pedagogy-related terms, limited to English-language articles at the final publication stage. Descriptive bibliometric indicators and four VOSviewer networks were analysed, covering author co-authorship, keyword co-occurrence, temporal keyword evolution, and document citation patterns. The corpus received 3,334 citations, averaging 13.83 citations per document, with 92.9% of articles cited at least once. The literature is concentrated in specialist journals, particularly the Journal of Chemical Education and Chemistry Education Research and Practice. Keyword analysis identified clusters involving teaching and students, undergraduate chemical education research, distance and computer-based learning, biomedical and instrument-oriented themes, and pedagogical content knowledge. Temporal patterns indicate a shift toward chemical education research, web-based learning, professional development, engagement, and pedagogical content knowledge, particularly following COVID-19. Co-authorship remains fragmented around small hubs. A focused analysis of 21 documents (2012–2026) further reveals an emerging neuro-pedagogical strand connecting neuroscience, learning science, cognitive load, emotion, stress, curiosity, and molecular representation. This underdeveloped intersection represents a promising frontier for future chemistry education research.

Corresponding Author:

Sofiyanita Sofiyanita,
Universitas Islam Negeri Sultan Syarif Kasim, Pekanbaru, Indonesia
Email: sofiyanita@uin-suska.ac.id

Introduction

Chemistry holds a demanding place within science education. Explaining the behaviour of matter requires learners to move fluently between what can be observed, the particulate models that account for it, and the symbolic language of formulas and equations. When these levels are not coordinated, knowledge remains fragile and disconnected, and the cognitive load of working across them at once is a long-standing explanation for why chemistry is experienced as difficult (Johnstone, 1991; Talanquer, 2011). The instructional problem is therefore not only which content is delivered but how teaching is organised so that conceptual, representational, and procedural understanding develop together. This places questions of teaching strategy and pedagogy at the centre of the discipline rather than at its edges.

Over the past two decades chemistry education research has matured from personal accounts of practice into an evidence-oriented field with its own theoretical commitments and methodological standards (Cooper & Stowe, 2018). As it has grown, its pedagogical vocabulary has diversified. Terms such as teaching strategy, teaching method, instructional strategy, teaching approach, and pedagogy now coexist with more specific constructs inquiry-based learning, collaborative learning, problem-based learning, flipped instruction, laboratory learning, and web-based learning, among others. Each carries assumptions about the learner, the role of the teacher, and the kind of chemical understanding being pursued (Seery, 2015; Sevian & Talanquer, 2014). Understanding how these constructs relate to one another is a prerequisite for cumulative progress.

The proliferation of pedagogical approaches has been accompanied by a broadening of the research agenda itself. Contemporary studies rarely treat teaching as an isolated act; they connect it to curriculum design, to the characteristics and identities of students, to laboratory work, to teacher education and professional development, to problem solving, and to scientific literacy (Shulman, 1986; Gilbert, 2006). Competency frameworks and evidence-based instructional reforms increasingly frame how instructional choices are justified and evaluated (Freeman et al., 2014). The result is a multidimensional literature in which pedagogical questions are entangled with questions about content, context, and outcomes.

One dimension of this multidimensional literature that is attracting growing but still scattered attention is the interface between chemistry teaching and neuroscience, an interface that operates in two directions. On the one hand, chemistry furnishes content that bears directly on the brain and behaviour neurotransmitters, psychopharmacology, and medicinal chemistry so that teaching strategies must meaningfully bridge the molecular and the mental (Hermanns et al., 2012; Mei & Yang, 2017; Godin et al., 2015). On the other, the very act of learning chemistry is a neurocognitive process: the cognitive load imposed by coordinating multiple levels of representation (Johnstone, 1991; Talanquer, 2011), the role of emotion and affective connection to content (Schmidt, 2020), the psychophysiologically measurable influence of stress (Hundertmark et al., 2019), and the curiosity and motivation that drive engagement (Kibga et al., 2021; Sunday et al., 2026). Aligning chemistry pedagogy with evidence about how the brain learns while guarding against ill-founded "brain-based" claims and neuromyths is a promising yet unconsolidated agenda (Graulich et al., 2026). The present study therefore also examines this neuro-pedagogical strand as part of a broader mapping.

This growth carries an unintended cost. Publications accumulate faster than any individual can synthesise, and the conceptual landscape which themes are central, which are peripheral, which are consolidating, and which are only beginning to form is hard to perceive through narrative reading. Bibliometric analysis addresses this difficulty directly. By treating publications, authors, keywords, and citations as a network, science mapping makes the structure of a field visible and supports claims about its development that are grounded in the record rather than in impression (Donthu et al., 2021; Zupic & Čater, 2015). Tools such as VOSviewer render these networks as interpretable maps of clusters, links, and temporal overlays (van Eck & Waltman, 2010).

Bibliometric studies of chemistry and science education already exist, but they tend either to survey the discipline broadly or to concentrate on a single technique. What remains comparatively underexplored is a focused mapping of the pedagogy-oriented segment of chemistry education the body of work explicitly organised around teaching strategies, teaching methods, instructional strategies, teaching approaches, and pedagogy examined as an intellectual structure with its own core, periphery, and emerging frontiers. The present study addresses this gap. It does not claim that no prior mapping exists; rather, it isolates a specific pedagogical corpus and analyses its network properties in detail so that the relationships among teaching, students, curriculum, and pedagogy can be characterised empirically. The corpus also spans the COVID-19 disruption, which offers a natural opportunity to observe how a rapid external shock reshaped the pedagogical agenda.

Accordingly, the study analyses 241 Scopus-indexed journal articles retrieved through a pedagogy-focused query and interprets the accompanying VOSviewer networks to answer five research questions: (RQ1) how research on chemistry education focusing on teaching strategies, teaching methods, instructional strategies, teaching approaches, and pedagogy has developed in Scopus-indexed journal articles; (RQ2) what the major thematic clusters and relationships characterising this research are; (RQ3) what the major intellectual foundations and highly influential studies underlying the field are; (RQ4) what emerging themes and directions can be identified from the temporal and thematic structure; and (RQ5) what research gaps and future opportunities can be derived from the bibliometric structure.

JPGI (Jurnal Penelitian Guru Indonesia)
Vol. 9, No. 4, 2024, pp. 72-89

Method

Research Design

This study uses a bibliometric research design. Bibliometrics applies quantitative techniques to bibliographic records in order to describe the structure and dynamics of a research field, and science mapping in particular visualises the relationships among its documents, authors, and concepts (Donthu et al., 2021; Aria & Cuccurullo, 2017). The design is descriptive and relational rather than experimental. It supports claims about how the literature is organised and how attention has shifted over time, but it does not establish causal relationships between pedagogical approaches and learning outcomes. To avoid overstating the design, the study is framed as a bibliometric analysis and not as a systematic review, since it does not synthesise individual study findings against a review protocol.

Data Source and Search Strategy

Scopus was used as the single data source because of its broad coverage of peer-reviewed education and chemistry journals and the completeness of its bibliographic and citation metadata, both of which are required for reliable science mapping (Zupic & Čater, 2015). The search combined the core concepts of the field with a family of pedagogy-related terms, using truncation to capture morphological variants:

chemistry AND education AND ("teaching strateg*" OR "teaching method*" OR "instructional strateg*" OR "teaching approach*" OR pedagogy)

The initial query returned 398 documents. Filters were then applied to obtain a homogeneous corpus of primary journal literature.

Inclusion and Exclusion Criteria

Records were retained if they were journal articles at the final publication stage written in English. Conference papers, reviews classified under other document types, book chapters, editorial material, and non-final records were excluded so that the analysis would rest on a consistent unit of publication. Applying these filters reduced the set to 241 records, which constitute the analysed corpus. Table 1 summarises the search and screening decisions.

Table 1 <Search strategy and inclusion/exclusion criteria.>

Parameter	Specification
Database	Scopus
Search field	Article title, abstract, keywords
Query	chemistry AND education AND ("teaching strateg*" OR "teaching method*" OR "instructional strateg*" OR "teaching approach*" OR pedagogy)
Initial records retrieved	398
Language filter	English
Publication stage filter	Final
Document type filter	Article
Source type filter	Journal
Records after screening (analysed corpus)	241
Analysis tools	Scopus analytics; VOSviewer (science mapping)

The screening pipeline can be read as a sequence: initial Scopus retrieval of 398 records, application of language, stage, document-type, and source-type filters, and reduction to 241 final journal articles, which then entered bibliometric computation, VOSviewer mapping, and interpretation. One observation must be reported transparently rather than concealed. Although screening returned 241 records and every record is a final-stage, English-language journal article, the publication years of the exported records span 2019 to 2023 rather than a narrower recent window; 159 records (66.0%) fall in 2021–2023 and 82 (34.0%) were published in 2019–2020. The analysis therefore treats N = 241 as the unit of analysis and reports the full 2019–2023 span, since the 2019–2020 cohort is analytically valuable: it captures the immediate pre-pandemic and early-pandemic baseline against which the pedagogical shifts observed later in the period can be read.

Bibliometric Analysis

Descriptive indicators were computed for the corpus, including annual publication and citation counts, the distribution of citations, the most productive authors, the most active source journals, the geographic distribution of contributing affiliations, and the frequency of author and index keywords. These indicators establish the size, productivity, and impact profile of the field and provide the quantitative backdrop against which the network maps are interpreted.

VOSviewer Analysis

Science mapping was performed with VOSviewer, which positions items so that strongly related items lie close together and assigns them to clusters through a modularity-based community-detection procedure (van Eck & Waltman, 2010). Four analyses are reported. In every map the size of a node reflects the weight of the item under the relevant analysis occurrences for keywords, documents produced for authors, and received citations for documents while lines represent co-occurrence, co-authorship, or citation links, and line thickness reflects the strength of the relationship. In the cluster views, colour denotes cluster membership; in the overlay views, colour denotes the average publication year according to the legend. Because exact VOSviewer weight values (total link strength and occurrence counts) were not exported with the maps, the interpretation describes relative size, centrality, and colour rather than inventing precise link-strength figures.

Research Questions

The five research questions structure the analysis: RQ1 is addressed through the descriptive and temporal indicators; RQ2 through keyword co-occurrence clustering; RQ3 through document citation analysis; RQ4 through the temporal overlay visualisations; and RQ5 through the synthesis of small, isolated, and weakly connected regions of the networks into a research agenda.

Complementary Focused Corpus for the Neuro Strand

To probe more deeply the neuro-pedagogical strand that surfaces at the periphery of the thematic network, a complementary focused corpus was examined separately from the main bibliometric corpus. This corpus was drawn from a Scopus export filtering documents at the intersection of chemistry and science teaching with neuro-related content and processes neurotransmitters, psychopharmacology, and medicinal chemistry, together with emotion, stress, curiosity, and representation in learning. The export returned 23 records; after removing one duplicate and one out-of-scope engineering-education record, 21 relevant documents published between 2012 and 2026 remained. Unlike the main corpus, this set is deliberately small and mixed in document type (articles, reviews, a book chapter, and a conference paper); it was therefore analysed qualitatively and as a scoping exercise rather than mapped as a network, and its counts were not merged into the bibliometric statistics of the 241-document corpus. Its purpose is illustrative and interpretive: to give concrete form to the neuro-pedagogical strand and to situate it relative to the pedagogical core already mapped. This boundary is stated transparently so that the complementary corpus is not misread as network-scale evidence.

Results and Discussions

Descriptive Overview of the Dataset

The 241 analysed articles have together attracted 3,334 citations, an average of 13.83 citations per document, and 224 of them (92.9%) have been cited at least once. The high proportion of cited documents indicates that the corpus is well integrated into the wider literature rather than dominated by unnoticed work, while the distribution remains skewed: the single most cited article carries 132 citations, and a small set of documents accounts for a disproportionate share of total impact. This pattern is characteristic of a productive specialty in which a few reference works anchor the discourse and the remainder contributes incrementally. The corpus is also strongly collaborative. Only 14.9% of articles are single-authored, 85.1% have two or more authors, and the mean is 3.37 authors per document, which indicates that pedagogical research in chemistry is generally conducted by teams.

Contributing affiliations are geographically wide but unevenly distributed. Ranked by the number of documents to which a country contributes at least one author affiliation, the United States is clearly dominant (64 documents), followed by China (14), Turkey and the United Kingdom (13 each), Brazil (11), and a cluster of systems contributing around ten documents each, including Spain, Australia, Germany, and India, with Indonesia (9), the Netherlands (7), and Saudi Arabia (6) also visible. The presence of several non-Western systems alongside the established Anglophone and European centres shows that pedagogical research in chemistry is a genuinely international enterprise, although formal cross-border co-authorship remains limited, since only 19.9% of articles involve authors from two or more countries.

Publication Development

Across the 2019–2023 span the corpus shows steady output with a clear inflection around the pandemic (Table 2). Annual production rises from 29 articles in 2019 to 53 in 2020, then settles at 49 in 2021 and 55 in both 2022 and 2023. Citation accumulation follows the expected inverse relation with recency: the 2020 cohort has attracted the most citations (994), followed by 2021 (806), while the most recent 2023 cohort, still new, has accumulated 422. The concentration of both output and impact in 2020–2021 is consistent with the surge of chemistry teaching studies prompted by the abrupt shift to emergency remote instruction, several of which became rapidly and heavily cited (Huang, 2020; Blizak et al., 2020; Babinčáková & Bernard, 2020). The divergence between later publication counts and their lower citation totals is a normal maturation signal rather than a decline in quality, and it cautions against reading recent low citation counts as evidence of low influence.

Table 2 <Annual publication and citation trends.>

Year	Articles	Citations	Cumulative articles
2019	29	537	29
2020	53	994	82
2021	49	806	131
2022	55	575	186
2023	55	422	241
Total	241	3,334	—

The most productive authors are listed in Table 3. Productivity is thin and evenly spread: no author contributes more than three articles to the corpus. Ingo Eilks, Claude Karegeya, John Sentongo, Seyhan Gencer, Huseyin Akkus, and Yezdan Boz each contribute three, and a longer tail of authors contributes two. The absence of a dominant author confirms at the level of individuals what the co-authorship map shows at the level of networks (Section 3.3): the field advances through many small contributions rather than through a few prolific programmes.

Table 3 <Most productive authors in the corpus.>

Rank	Author	Articles
1	Eilks, I.	3
2	Karegeya, C.	3
3	Sentongo, J.	3
4	Gencer, S.	3
5	Akkus, H.	3
6	Boz, Y.	3
7	Rahmawati, Y.	2
8	Anderson, T. R.	2
9	Huwer, J.	2
10	Marques, C. A.	2

Publication is concentrated in a small number of specialist outlets. The Journal of Chemical Education alone accounts for 61 of the 241 articles, followed by Chemistry Education Research and Practice (14), Biochemistry and Molecular Biology Education (9), Chemistry Teacher International (8), and Education Sciences and the Eurasia Journal of Mathematics, Science and Technology Education (7 each). This concentration means that the discourse on chemistry teaching is shaped by the editorial priorities of a handful of dedicated venues, which lends coherence to the field but also channels how pedagogical questions are framed and reported.

Co-authorship Analysis

The co-authorship network of authors is shown in Figure 1. Rather than a single integrated research community, the map shows a set of small, largely disconnected components. The largest visible groupings are compact: a red clique links Nadia Chafiq and Kamal Moundy with several co-authors; cyan connects Yuli Rahmawati with Elisabeth Taylor; a blue triad joins Wilfried Admiraal and Jan van Driel; an orange group forms around Claude Karegeya; and a green pair links Maija Aksela with Lizethly Cáceres-Jensen. Many otherwise productive authors Yezdan Boz, Ingo Eilks, Huseyin Akkus, Johannes Huwer, Ron Blonder appear as isolated nodes or small dyads with no visible link to the others. Node sizes are modest and comparable throughout, consistent with the low per-author productivity reported above.

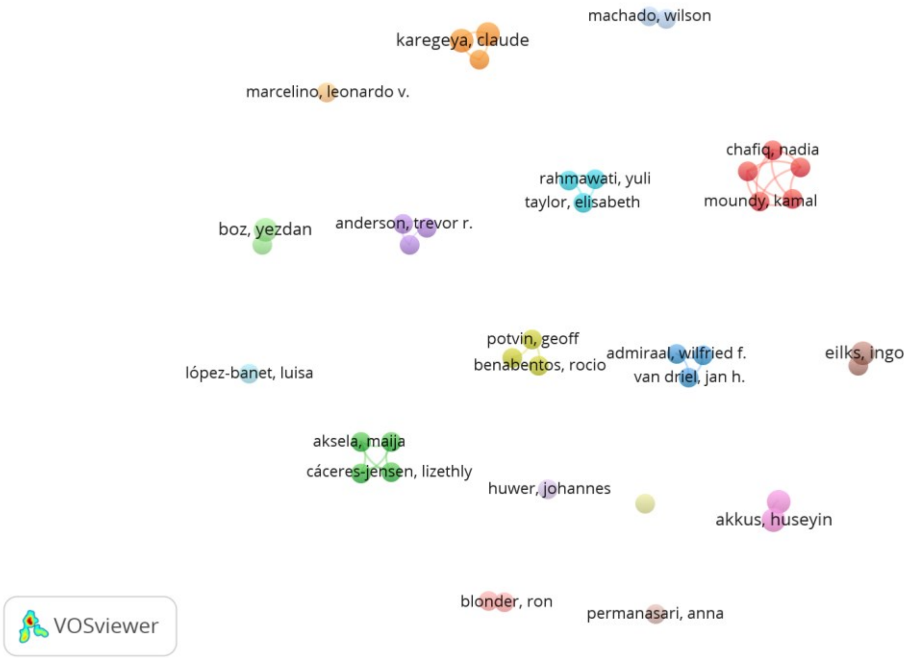

Figure 1 <Co-authorship network of authors>

This fragmentation is a substantive finding rather than a cosmetic one. It indicates that the field advances through many parallel research lines anchored by individual groups or national teams rather than through a densely interconnected invisible college. Such a structure brings diversity of approach and local responsiveness, but it also implies limited cross-pollination, duplicated effort, and slow consolidation of methods. For a field whose credibility rests on cumulative evidence (Cooper & Stowe, 2018), the weak connectivity between productive authors is precisely the kind of structural feature that a research-capacity strategy could target, and it helps explain why the same pedagogical constructs are repeatedly re-investigated in isolation.

Keyword Co-occurrence Analysis

The keyword co-occurrence network is shown in Figure 2, coloured by cluster. The most frequent author keywords are chemistry education (28 occurrences), chemical education research (20), first-year undergraduate/general chemistry (20), collaborative/cooperative learning (17), and pedagogy (14), followed by student-centered learning, distance learning/self instruction, higher education, and chemistry (12 each) and by curriculum, laboratory instruction, internet/web-based learning, and second-year undergraduate (11 each). Among index keywords, teaching (28), education (20), curriculum (18), students (17), and learning (16) dominate, alongside a strong biomedical vocabulary (human, humans, biochemistry, molecular biology, metabolism) inherited from the health-science journals that the query also captured. The network is dense at its centre and resolves into several interpretable clusters (Table 6).

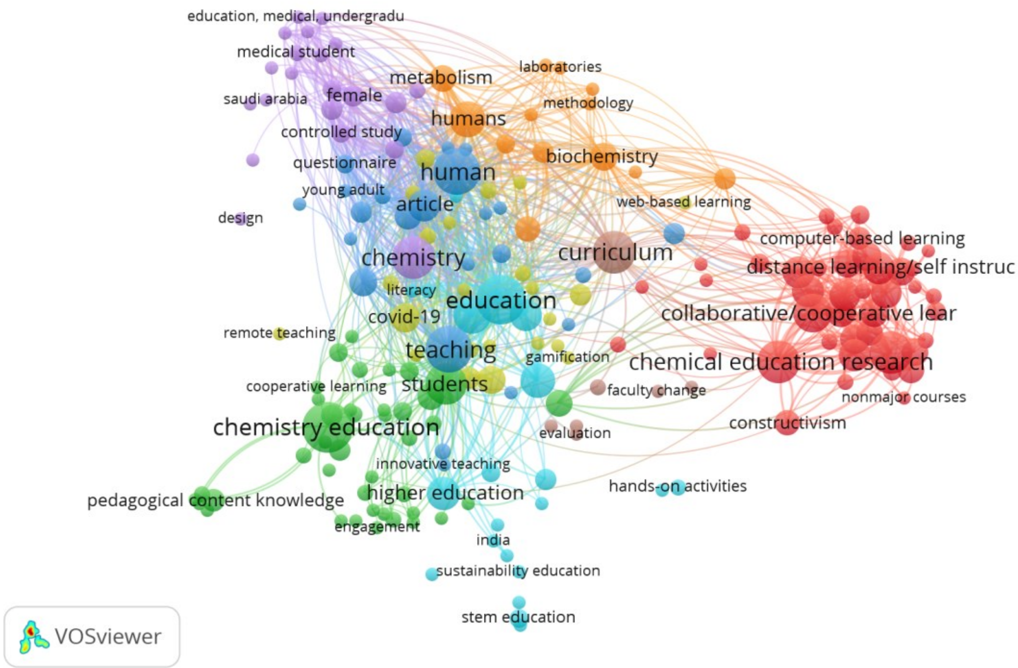

Figure 2 <Keyword co-occurrence network>

Four to five conceptual regions can be read from the map. A central teaching–student cluster (teaching, students, education, higher education, COVID-19, gamification, evaluation) occupies the core and links to every other region, marking it as the connective tissue of the field. A chemistry-education and pedagogical-content-knowledge cluster (chemistry education, pedagogical content knowledge, cooperative learning, engagement, innovative teaching, STEM education, sustainability education) sits adjacent to it and carries the discipline-specific pedagogical identity of the corpus. A distinct undergraduate chemical-education-research cluster on the right (chemical education research, collaborative/cooperative learning, distance learning/self instruction, computer-based learning, constructivism, nonmajor courses) groups the practice-oriented, technology-enabled instruction typical of first-year and non-major courses. A curriculum-and-biomedical cluster (curriculum, biochemistry, humans, metabolism, laboratories, methodology, web-based learning) bridges chemistry teaching to the health-science context, and a peripheral biomedical-descriptor cluster (human, female, questionnaire, medical student, controlled study) sits at the edge with weaker links to the pedagogical core. The pedagogy-specific terms that motivated the search teaching strategy, teaching methods, instructional approaches appear as mid-sized nodes distributed across the central and chemistry-education clusters rather than forming a cluster of their own, which suggests that pedagogy in this corpus is expressed through concrete approaches (collaborative, inquiry, flipped, laboratory, and web-based learning) rather than as an abstract standalone theme.

Citation Analysis

The document citation overlay is shown in Figure 4 and the most cited documents in Table 4. Unlike broad chemistry-education maps in which decades-old works dominate, the intellectual base of this corpus is recent and tightly bound to the pandemic. The largest node is Chan et al. (2021), a systematic review of virtual chemical laboratories (132 citations), which functions as a bridging reference between laboratory pedagogy and digital instruction. It is surrounded by a cohort of 2020–2021 studies on emergency remote teaching and online laboratories Huang (2020) on online chemistry teaching in China (106), Babinčáková and Bernard (2020) on online experimentation (85), Kelley (2021) on laboratory learning during COVID-19 (78), and Blizak et al. (2020) on students' perceptions of the transition to online learning (73). Newer high-impact nodes such as Doğan et al. (2023) on flipped classrooms (60) and Rahmawati et al. (2022) on engagement for sustainability (56) extend the base toward synthesis and student-centred innovation.

Table 4 <Most cited documents in the corpus.>

Rank	Document	Year	Citations
1	Chan et al. – Virtual chemical laboratories (systematic review)	2021	132
2	Huang – Online teaching of chemistry in China during COVID-19	2020	106
3	Babinčáková & Bernard – Online experimentation during closures	2020	85
4	Kelley – LAB theory and laboratory learning during COVID-19	2021	78
5	Blizak et al. – Perceptions of transition to online learning	2020	73
6	Doğan et al. – Effectiveness of flipped classroom practices	2023	60
7	Rahmawati et al. – Engagement in education as sustainability	2022	56
8	Mutambuki et al. – Metacognition and active learning	2020	48
9	Falah et al. – Virtual reality gamification	2021	46
10	Correia et al. – PhET simulation for submicroscopic level	2019	45
11	Avargil et al. – Educational escape room	2021	44
12	Vogelzang et al. – Scrum methodology as scaffold	2019	42

Two points follow. First, the citation structure confirms that the field's current intellectual foundation is not a set of classic theoretical works but a wave of pandemic-era empirical studies on digital and laboratory teaching; older foundational ideas (Johnstone, 1991; Shulman, 1986) remain influential conceptually but are cited from outside the corpus rather than as its most-cited members. Second, several highly cited documents Chan et al. (2021), Correia et al. (2019), Falah et al. (2021) sit at the interface between pedagogy and technology, occupying bridging positions that tie the teaching core to the digital-learning periphery. Table 5 reports the most frequent keywords that underpin these thematic readings.

Table 5 <Most frequent author and index keywords.>

Rank	Author keyword	Occ.	Index keyword	Occ.
1	chemistry education	28	teaching	28
2	chemical education research	20	education	20
3	first-year undergraduate/general	20	curriculum	18
4	collaborative/cooperative learning	17	students	17
5	pedagogy	14	learning	16
6	student-centered learning	12	biochemistry	13
7	distance learning/self instruction	12	student	11
8	higher education	12	chemistry	8
9	curriculum	11	teaching methods	5
10	laboratory instruction	11	COVID-19	5

Thematic Evolution and Emerging Research Topics

The keyword overlay in Figure 3 colours each term by its average publication year and makes the movement of attention across the period legible. The temporal distribution indicates three broad layers. The earliest layer (toward the blue end of the legend) is occupied by biomedical and instrument descriptors human, humans, female, biochemistry, metabolism, medical student, questionnaire, controlled study reflecting the health-science strand that entered the corpus through cross-listed journals. A middle, transitional layer contains the disciplinary and instructional core education, teaching, students, chemistry, chemistry education, curriculum, higher education which sits at the temporal centre of gravity of the field. The most recent layer (toward the yellow end) is occupied by chemical education research, remote teaching, pedagogical content knowledge, engagement, gamification, sustainability education, and design, suggesting that the field's attention has moved toward research-oriented, technology-enabled, and competency-oriented framings.

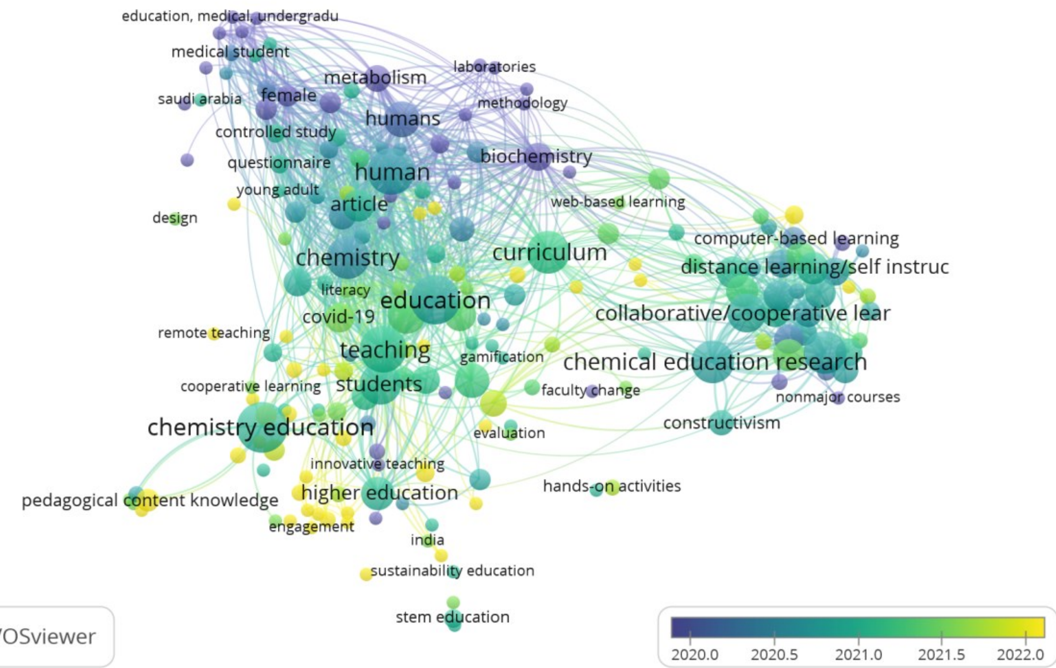

Figure 3 <Keyword overlay visualisation showing temporal development>

Read together with the citation overlay, this pattern points toward a pedagogical landscape reshaped by the pandemic and its aftermath. The overlay visualisation suggests that emergency remote teaching acted as a catalyst: terms tied to distance, web-based, and gamified instruction move to the recent end of the spectrum, while generic "teaching chemistry" vocabulary sits earlier. The findings point toward consolidation around chemical education research as a self-aware research identity, and toward the growth of pedagogical content knowledge, engagement, and sustainability as competency-oriented frontiers. These readings are interpreted as indications of directional change rather than as causal evidence, in keeping with the descriptive nature of overlay mapping. Table 7 organises the terms into established, transitional, and emerging themes on this basis.

Intellectual Structure of Chemistry Education Research

Taken together, the four maps describe an intellectual structure with a dense pedagogical core, a technology-and-practice frontier, and a loosely attached biomedical periphery. The keyword clusters (Table 6) define the conceptual regions of the field; the citation network identifies its current empirical foundations; the overlay locates these regions in time; and the co-authorship map shows how thinly the human network that produces them is connected. The core is organised around teaching, students, chemistry education, and curriculum, with pedagogy realised through concrete approaches rather than as an abstract theme. The frontier is defined by distance, web-based, and laboratory learning together with chemical education research as a reflexive identity. The periphery the biomedical descriptor cluster is only weakly tied to the pedagogical core, marking a boundary of the field rather than a growth area. This structure directly informs the discussion and the research agenda that follow.

Table 6 <Thematic clusters identified from keyword co-occurrence.>

Cluster	Representative keywords	Interpretation
C1. Teaching–student core	teaching, students, education, higher education, COVID-19, gamification, evaluation	Connective core linking all regions; generic instruction and its evaluation
C2. Chemistry education & PCK	chemistry education, pedagogical content knowledge, cooperative learning, engagement, innovative teaching, STEM/sustainability education	Discipline-specific pedagogical identity and teacher knowledge
C3. Undergraduate CER & digital	chemical education research, collaborative/cooperative learning, distance & computer-based learning, constructivism, nonmajor courses	Practice-oriented, technology-enabled undergraduate instruction

C4. Curriculum & biomedical bridge	curriculum, biochemistry, humans, metabolism, laboratories, methodology, web-based learning	Bridge from chemistry teaching to health-science context
C5. Biomedical descriptors (periphery)	human, female, questionnaire, medical student, controlled study, young adult	Loosely attached edge inherited from cross-listed journals

Table 7 <Emerging, transitional, and established research themes.>

Status	Themes	Temporal signal
Established	teaching, students, chemistry, education, curriculum, biochemistry, questionnaire	Earlier / central average year
Transitional	chemistry education, higher education, laboratory instruction, collaborative learning, problem solving	Mid-period average year
Emerging	chemical education research, remote/distance learning, pedagogical content knowledge, engagement, gamification, sustainability education	Recent average year

Complementary Focused Corpus: The Neuro-Oriented Strand

The 21 documents of the complementary corpus have together attracted 183 citations (mean 8.0 per document), the most influential being a virtual-laboratory study for correcting molecular-symmetry misconceptions (Achuthan et al., 2018; 45 citations) and a pharmacology-based enrichment programme that cultivated interest in science (Godin et al., 2015; 15 citations). Its annual distribution leans toward the recent period nine documents appeared in 2024–2026 which suggests that the strand has gathered momentum only lately. In terms of content, the documents fall into three complementary strands.

The first concerns chemistry content that intersects directly with neuroscience and pharmacology. Here one finds the use of music to teach psychopharmacology concepts and to name neurotransmitters (Hermanns et al., 2012), the deployment of Vincent van Gogh's illness narratives to revise medicinal-chemistry learning (Mei & Yang, 2017), and an interdisciplinary pharmacology-based enrichment programme (Godin et al., 2015). This strand demonstrates that brain-related content can serve as a meaningful context binding molecules to mental function.

The second strand concerns the science of learning the neurocognitive and affective dimensions of how chemistry is learned. It includes a psychophysiological study of near-peer tutors' stress through cortisol and heart-rate variability (Hundertmark et al., 2019), the influence of emotional connection on approaches to learning (Schmidt, 2020) and the role of emotion in game-based learning (Girmay et al., 2026), the cultivation of curiosity through hands-on activity (Kibga et al., 2021), the predictive interplay of concept maps, prior knowledge, and motivational variables on outcomes (Sunday et al., 2026), reflection and critical reasoning (Cha et al., 2016), and the modelling of the visual complexity of molecules, which bears on the cognitive load of representations (Markovnikova et al., 2024). The third strand concerns epistemic caution: a recent review dismantling myths about the teaching and learning of organic chemistry (Graulich et al., 2026) and the use of multiple-intelligence theory as an instance of a cognition-oriented claim that warrants critical appraisal rather than wholesale adoption (Guzel & Coskun, 2013). The remaining documents display the broader pedagogical repertoire in which this neuro strand is nested game-based learning for chemical bonding (Debit et al., 2024), hands-on inquiry in physical chemistry (Deng et al., 2023), artificial intelligence in the chemistry classroom (Abbas et al., 2024), inquiry-based learning of proteomics and metabolomics (Nezhyva et al., 2024), student-centred methods (Yoder et al., 2021), creativity in the digital era (Pagliaro, 2019), a meta-analysis of argumentation (Fu & Zhan, 2026), and a philosophical account of emergent molecular properties (Vivas-Reyes et al., 2024). Table 9 summarises the core neuro-pedagogical strands.

Table 8 <Neuro-pedagogical strands in the complementary focused corpus.>

Strand	Focus	Representative documents
S1. Neuro/pharmacology content	Neurotransmitters, psychopharmacology, medicinal chemistry	Hermanns et al. (2012); Mei & Yang (2017); Godin et al. (2015)
S2. Science of learning	Stress, emotion, curiosity,	Hundertmark et al. (2019); Schmidt (2020);

(cognitive–affective)	motivation, perceptual load of representations	Girmay et al. (2026); Kibga et al. (2021); Sunday et al. (2026); Cha et al. (2016); Markovnikova et al. (2024)
S3. Epistemic caution	Learning myths / brain-based claims	Graulich et al. (2026); Guzel & Coskun (2013)

Dominant Research Themes

The mapping shows that the field is organised around a compact set of core themes teaching, students, chemistry education, chemistry, education, and curriculum that occupy the densest part of the network and connect to every peripheral region. This confirms, with network evidence, the long-standing claim that instruction in chemistry cannot be separated from the content and the learner it serves (Johnstone, 1991; Talanquer, 2011). The prominence of curriculum as a central rather than peripheral node is notable: it indicates that pedagogical questions in this corpus are routinely framed as curricular questions, so that decisions about teaching strategy are tied to decisions about sequence, coherence, and what counts as chemical understanding (Sevian & Talanquer, 2014). For practitioners this implies that isolated method changes are unlikely to succeed unless they are aligned with curricular goals.

Evolution of Teaching Strategies and Pedagogical Approaches

The temporal overlay indicates a shift from generic teaching vocabulary toward specific, evidence-based approaches, and the citation base shows which approaches have gained traction. Active learning, metacognition, and inquiry-oriented designs recur among the more cited studies (Mutambuki et al., 2020; Vincent-Ruz et al., 2020; Treagust et al., 2020), consistent with meta-analytic evidence that active engagement outperforms transmission teaching across STEM (Freeman et al., 2014). Flipped and peer-led formats appear as a distinct and growing strand (Doğan et al., 2023; Jang & Kim, 2020; Stephenson et al., 2019; Houseknecht et al., 2020), extending the flipped-learning trajectory earlier identified for chemistry (Seery, 2015). The pattern suggests that "pedagogy" in chemistry education is now enacted through a repertoire of concrete, student-active designs rather than invoked as a general principle, which is a healthy sign of methodological maturation but also a source of fragmentation when each design is studied in isolation.

Relationship Between Teaching, Students, Curriculum, and Pedagogy

The clustering places teaching, students, and curriculum in the connective core while pedagogy and pedagogical content knowledge sit in the adjacent discipline-specific cluster. This arrangement is theoretically coherent: pedagogical content knowledge is precisely the construct that binds general teaching to subject-specific curriculum, translating what teachers know about chemistry into decisions about how to teach it (Shulman, 1986). The corpus operationalises this link concretely, with several studies developing and measuring PCK and TPACK in pre-service and in-service chemistry teachers (Goes et al., 2020; Oztay & Boz, 2022; Can-Kucuk et al., 2022; Zimmermann et al., 2021; Widyasari et al., 2022). The centrality of context-oriented curriculum terms further echoes the argument that chemical concepts are best taught through meaningful contexts rather than in the abstract (Gilbert, 2006). Together these results indicate that the teaching–student–curriculum–pedagogy relationship is not merely conceptual in this literature but is actively instrumented through teacher-knowledge research.

Digital, Laboratory, Problem-Based, and Student-Centered Directions

The most cited and most recent regions of the maps converge on technology-enabled and laboratory pedagogy. The pandemic forced a rapid re-examination of how practical chemistry can be taught at a distance, and the corpus registers this as a surge of work on online experimentation, remote laboratories, and virtual and simulation-based practice (Huang, 2020; Blizak et al., 2020; Babinčáková & Bernard, 2020; Díez-Pascual & Jurado-Sánchez, 2022; Correia et al., 2019; Chan et al., 2021). Laboratory instruction, far from being displaced, is reconceptualised through frameworks for what laboratory learning is meant to achieve (Kelley, 2021). Gamified and game-based designs escape rooms, virtual-reality environments, just-in-time laboratory games — emerge as a lively sub-frontier (Avargil et al., 2021; Falah et al., 2021; Llanos et al., 2021). Problem-based and scaffolded student-centred approaches remain well represented (Valdez & Bungihan, 2019; Vogelzang et al., 2019; Flener-Lovitt et al., 2020). The implication is that the digital turn in chemistry teaching is not a temporary pandemic artefact but has been absorbed into the field's repertoire, reshaping the pedagogical landscape toward blended, active, and technology-mediated practice.

Emerging Research Frontiers

Three frontiers stand out where recency, rising citations, and cluster position coincide. The first is the consolidation of chemical education research as a reflexive identity, visible as a large recent node that increasingly names the field's own methods and standards (Cooper & Stowe, 2018). The second is the coupling of pedagogy with competency and citizenship goals, expressed through engagement, scientific literacy, and sustainability education (Rahmawati et al., 2022; Georgiou & Kyza, 2023; Vogelzang et al., 2020), and in the development of student self-efficacy and science identity through authentic research experiences (Wilczek et al., 2022). The third is the professionalisation of teaching capacity, seen in work on faculty development, teaching-assistant training, and evidence-based reform (Biswas et al., 2022; Lang et al., 2020). Argument-focused and writing-to-learn designs (Aguirre-Mendez et al., 2020) and context-based green-chemistry teaching (Marcelino et al., 2023; Ahmad et al., 2023) round out the emerging edge. These frontiers share a move from asking whether a method works to asking how teaching capacity and disciplinary literacy can be built at scale.

Research Gaps and Future Research Agenda

Several gaps are legible directly from the network structure rather than from opinion. The co-authorship fragmentation (Figure 1) signals a capacity gap: productive authors rarely collaborate across groups, which slows the accumulation and replication that a maturing field requires. The keyword map reveals a conceptual gap between pedagogical-innovation terms (gamification, flipped, distance learning) and chemistry-specific conceptual nodes (chemical bonding, stoichiometry, and related content), which sit in different regions and are only weakly linked the mapping reveals an underexplored connection between pedagogical innovation and chemistry-specific conceptual learning. A third gap concerns outcomes: teaching-strategy terms co-occur strongly with implementation but weakly with sustained learning-outcome and transfer measures, so the link between pedagogical design and durable conceptual gain is thinly evidenced. The biomedical periphery, though present, remains disconnected from the pedagogical core and represents a boundary rather than an opportunity. Table 8 translates these observations into a concrete agenda.

Table 9 <Research agenda derived from identified gaps.>

No.	Gap identified from the bibliometric structure	Proposed future research direction
1	Weak link between pedagogical innovation and chemistry-specific concepts	Design studies integrating flipped, gamified, or digital methods with chemical bonding, stoichiometry, and equilibrium learning
2	Teaching strategy co-occurs with implementation, weakly with outcomes	Studies connecting teaching strategy to problem solving, scientific literacy, and durable learning gains
3	Rapid but under-consolidated digital/laboratory turn	Comparative and longitudinal studies of virtual, remote, and hands-on laboratory pedagogy beyond the pandemic
4	Laboratory pedagogy reframed but not yet theorised	Development of learning-goal frameworks for laboratory instruction across course levels
5	Professionalisation frontier still thin	Longitudinal evaluation of teacher and faculty professional development on chemistry teaching quality
6	Student-centred designs studied in isolation	Assessment of pedagogical interventions with common outcome measures to enable synthesis
7	Fragmented co-authorship network	Cross-group and cross-national collaborative programmes and shared instruments
8	Limited international co-authorship (19.9%)	Cross-cultural comparative studies of pedagogy across educational systems
9	Small, fragmented neuro-pedagogical strand	Systematic programmes integrating neuroscience content (neurotransmitters, psychopharmacology) with context-based chemistry pedagogy
10	Science of learning not linked to chemistry instruction design	Studies connecting cognitive load, emotion, stress, and curiosity to chemistry-specific conceptual gains, with explicit screening of neuromyths

The Neuro-Pedagogical Frontier in Chemistry Education

The complementary corpus brings into focus a frontier only faintly visible in the main thematic network: the intersection of chemistry pedagogy and neuroscience. This frontier matters because it couples two concerns that have largely been treated apart brain-related chemistry content and the neurocognitive processes that underpin the learning of chemistry. On the content side, teaching neurotransmitters and psychopharmacology through an engaging medium such as music (Hermanns et al., 2012), or through clinical and biographical narrative in medicinal chemistry (Mei & Yang, 2017), shows that brain-related topics can function as meaningful contexts that bridge the submicroscopic level and human experience precisely the cross-level bridging that classical frameworks identify as decisive for success in learning chemistry (Johnstone, 1991; Talanquer, 2011). A pharmacology-based enrichment programme that heightened interest in science (Godin et al., 2015) reinforces the argument that neuro content can serve as a motivational gateway into chemistry.

On the process side, the complementary corpus links chemistry pedagogy to the science of learning more explicitly than the main corpus does. Psychophysiological evidence on stress through cortisol and heart-rate variability indicates that the neurophysiological state of learners and tutors is not a neutral backdrop to instruction (Hundertmark et al., 2019). Emotional connection to content shapes the learning approaches students adopt (Schmidt, 2020), and the emotions elicited by game-based design form part of its learning mechanism rather than mere ornament (Girmay et al., 2026). Curiosity cultivated through hands-on activity (Kibga et al., 2021) and the interplay of concept maps, prior knowledge, and motivational variables (Sunday et al., 2026) connect affect and cognition to outcomes. Reflection and critical reasoning (Cha et al., 2016) and the modelling of molecular visual complexity (Markovnikova et al., 2024) bear directly on the representational cognitive load that lies at the heart of chemistry's difficulty, thereby dovetailing with the metacognition and active-learning findings of the main corpus (Mutambuki et al., 2020; Freeman et al., 2014). Virtual-laboratory simulations designed to correct misconceptions (Achuthan et al., 2018) confirm that conceptual change is a target that can be pursued deliberately.

This frontier demands epistemic care. A recent review dismantling myths about the teaching and learning of organic chemistry cautions that many circulating "brain-based" beliefs lack an evidentiary foundation (Graulich et al., 2026), while popular frameworks such as multiple-intelligence theory warrant critical appraisal rather than application as recipe (Guzel & Coskun, 2013). The implication is clear: integrating neuroscience into chemistry pedagogy has the potential to enrich instructional design from the choice of content context to the management of cognitive load, emotion, and motivation but only if neuroscientific claims are filtered through appropriate evidence on learning and are not reduced to neuromyths. Because the strand remains small, recent, and only loosely tethered to the pedagogical core, it is best read as a promising frontier warranting systematic development rather than as an established field.

Conclusions

This study mapped the pedagogy-focused segment of chemistry education across 241 Scopus-indexed journal articles published between 2019 and 2023. In answer to RQ1, the field grew steadily with a pandemic-driven inflection in 2020–2021 and is concentrated in a few specialist journals led by the Journal of Chemical Education. In answer to RQ2, the literature is organised around a dense teaching–student–curriculum core, a discipline-specific chemistry-education and PCK cluster, a technology-enabled undergraduate research cluster, and a loosely attached biomedical periphery, with pedagogy realised through concrete approaches rather than as an abstract theme. In answer to RQ3, the current intellectual foundation is a recent cohort of empirical studies on online, remote, and laboratory teaching, bridged by systematic reviews such as Chan et al. (2021), while classic conceptual works remain influential from outside the corpus. In answer to RQ4, the overlay analysis points toward chemical education research, distance and web-based learning, professional development, engagement, and sustainability as emerging frontiers. In answer to RQ5, the network exposes gaps in the coupling of pedagogical innovation to chemistry-specific learning, in the measurement of durable outcomes, and in cross-group collaboration, from which a concrete research agenda was derived. The As a further probe, examination of the complementary focused corpus disclosed a neuro-pedagogical frontier linking neuroscience-related chemistry content to the science of learning; this strand is small, recent, and uncultivated, and so marks a clear opportunity rather than an established field. The study's contribution is to make these relationships visible and to convert them into actionable directions grounded in the record.

For researchers, the results argue for deliberately linking pedagogical-innovation studies to chemistry-specific conceptual learning and to durable outcome measures, and for building shared instruments so that isolated intervention studies can be synthesised. The fragmented co-authorship structure suggests concrete value in cross-group and cross-national programmes that pool expertise rather than re-investigating the same designs separately. For teacher educators and curriculum designers, the centrality of curriculum and pedagogical content knowledge implies that method reforms should be embedded in curricular and teacher-knowledge development rather than adopted as standalone techniques (Shulman, 1986; Sevian & Talanquer, 2014). For practitioners, the consolidation of active, blended, and laboratory-oriented approaches offers an evidence-informed repertoire, provided that technology is used in service of conceptual understanding rather than as an end in itself. For editors and funders, the concentration of the field in a few venues and the thin collaboration network indicate where infrastructure investment could most improve consolidation.

Several limitations qualify these findings. The analysis draws on a single database, Scopus; although its coverage of chemistry and education journals is extensive, relevant work indexed only elsewhere is not represented, and the query's reliance on specific pedagogical terms may have excluded studies that use different vocabulary. The corpus spans 2019–2023 rather than a single window, so temporal claims describe this five-year span and should not be extrapolated beyond it. Bibliometric mapping is descriptive and relational: node sizes, clusters, and overlays summarise association and attention, not causation, and the exact VOSviewer weight values were not available, so the interpretation used relative rather than absolute measures. Author disambiguation and the country-attribution procedure rely on the metadata as exported and may contain minor inaccuracies. The complementary focused corpus for the neuro strand is small (21 documents), mixed in document type, and examined qualitatively; its findings are therefore illustrative and cannot be generalised in the way the network-scale results of the main corpus can. Finally, cluster boundaries in VOSviewer depend on resolution settings, so the thematic structure should be read as a robust approximation rather than a fixed partition. These constraints temper the strength of the conclusions without undermining the structural patterns, which are consistent across the four independent maps.

References

Abbas, T., Javed, U., Mehmood, F., Raza, M., & Li, H. (2024). ChemGenX: AI in the chemistry classroom. In ACM International Conference Proceeding Series (pp. 224–230). https://doi.org/10.1145/3700297.3700336

Achuthan, K., Kolil, V. K., & Diwakar, S. (2018). Using virtual laboratories in chemistry classrooms as interactive tools towards modifying alternate conceptions in molecular symmetry. Education and Information Technologies, 23(6), 2499–2515. https://doi.org/10.1007/s10639-018-9727-1

Aguirre-Mendez, C., Chen, Y.-C., Terada, T., & Techawitthayachinda, R. (2020). Predicting components of argumentative writing and achievement gains in a general chemistry course. Journal of Chemical Education, 97(8), 2045–2056. https://doi.org/10.1021/acs.jchemed.0c00042

Ahmad, Z., Ammar, M., Sellami, A., & Al-Thani, N. J. (2023). Effective pedagogical approaches used in high school chemistry education: A systematic review. Journal of Chemical Education, 100(5), 1796–1810. https://doi.org/10.1021/acs.jchemed.2c00739

Aria, M., & Cuccurullo, C. (2017). bibliometrix: An R-tool for comprehensive science mapping analysis. Journal of Informetrics, 11(4), 959–975. https://doi.org/10.1016/j.joi.2017.08.007

Avargil, S., Shwartz, G., & Zemel, Y. (2021). Educational escape room: Break Dalton's code and escape! Journal of Chemical Education, 98(7), 2313–2322. https://doi.org/10.1021/acs.jchemed.1c00110

Babinčáková, M., & Bernard, P. (2020). Online experimentation during COVID-19 secondary school closures: Teaching methods and students' experiences. Journal of Chemical Education, 97(9), 3295–3300. https://doi.org/10.1021/acs.jchemed.0c00748

Biswas, S., Benabentos, R., Brewe, E., Potvin, G., Edward, J., Kravec, M., & Kramer, L. (2022). Institutionalizing evidence-based STEM reform through faculty professional development and support structures. International Journal of STEM Education, 9(1), 36. https://doi.org/10.1186/s40594-022-00353-z

Blizak, D., Blizak, S., Bouchenak, O., & Yahiaoui, K. (2020). Students' perceptions regarding the abrupt transition to online learning during the COVID-19 pandemic. Journal of Chemical Education, 97(9), 2466–2471. https://doi.org/10.1021/acs.jchemed.0c00668

Can-Kucuk, D., Gencer, S., & Akkus, H. (2022). Development of pre-service chemistry teachers' pedagogical content knowledge through a teaching practicum. Chemistry Education Research and Practice, 23(3), 599–615. https://doi.org/10.1039/d2rp00033d

Cha, J., Kan, S.-Y., & Chia, P. W. (2016). College students' reflection on the uncritical inference test activity in an organic chemistry course. Journal of the Korean Chemical Society, 60(2), 137–143. https://doi.org/10.5012/jkcs.2016.60.2.137

Chan, P., Van Gerven, T., Dubois, J.-L., & Bernaerts, K. (2021). Virtual chemical laboratories: A systematic literature review of research, technologies and instructional design. Computers and Education Open, 2, 100053. https://doi.org/10.1016/j.caeo.2021.100053

Cooper, M. M., & Stowe, R. L. (2018). Chemistry education research—From personal empiricism to evidence, theory, and informed practice. Chemical Reviews, 118(12), 6053–6087. https://doi.org/10.1021/acs.chemrev.8b00020

Correia, A.-P., Koehler, N., Thompson, A., & Phye, G. (2019). The application of PhET simulation to teach gas behavior on the submicroscopic level. Research in Science and Technological Education, 37(2), 193–217. https://doi.org/10.1080/02635143.2018.1487834

Debit, J. S. P., Bacoba, H. M. P., Tabanao, M. M. C., & Walag, A. M. P. (2024). GamesBond: A game-based supplemental teaching material for ionic and covalent bonding. Journal of Chemical Education, 101(4), 1610–1617. https://doi.org/10.1021/acs.jchemed.3c01265

Deng, X., Zhao, J., Tian, Q., & Wang, H. (2023). Applying hands-on inquiry learning in physical chemistry teaching practice to improve teaching quality. Indian Journal of Pharmaceutical Education and Research, 57(4), 1175–1182. https://doi.org/10.5530/ijper.57.4.140

Donthu, N., Kumar, S., Mukherjee, D., Pandey, N., & Lim, W. M. (2021). How to conduct a bibliometric analysis: An overview and guidelines. Journal of Business Research, 133, 285–296. https://doi.org/10.1016/j.jbusres.2021.04.070

Doğan, Y., Batdı, V., & Yaşar, M. D. (2023). Effectiveness of flipped classroom practices in teaching of science: A mixed research synthesis. Research in Science and Technological Education, 41(1), 393–421. https://doi.org/10.1080/02635143.2021.1909553

Díez-Pascual, A. M., & Jurado-Sánchez, B. (2022). Remote teaching of chemistry laboratory courses during COVID-19. Journal of Chemical Education, 99(5), 1913–1922. https://doi.org/10.1021/acs.jchemed.2c00022

Falah, J., Wedyan, M., Alfalah, S. F. M., Abu-Tarboush, M., Al-Jakheem, A., Al-Faraneh, M., Abuhammad, A., & Charissis, V. (2021). Identifying the characteristics of virtual reality gamification for complex educational topics. Multimodal Technologies and Interaction, 5(9), 53. https://doi.org/10.3390/mti5090053

Flener-Lovitt, C., Bailey, K., & Han, R. (2020). Using structured teams to develop social presence in asynchronous chemistry courses. Journal of Chemical Education, 97(9), 2519–2525. https://doi.org/10.1021/acs.jchemed.0c00765

Freeman, S., Eddy, S. L., McDonough, M., Smith, M. K., Okoroafor, N., Jordt, H., & Wenderoth, M. P. (2014). Active learning increases student performance in science, engineering, and mathematics. Proceedings of the National Academy of Sciences, 111(23), 8410–8415. https://doi.org/10.1073/pnas.1319030111

Fu, X., & Zhan, Q. (2026). Effectiveness of argument in science education: A meta-analysis based on the results of 17 experiments. Research in Science and Technological Education, 44(2), 469–489. https://doi.org/10.1080/02635143.2025.2527603

Georgiou, Y., & Kyza, E. A. (2023). Fostering chemistry students' scientific literacy for responsible citizenship through socio-scientific inquiry-based learning. Sustainability, 15(8), 6442. https://doi.org/10.3390/su15086442

Gilbert, J. K. (2006). On the nature of context in chemical education. International Journal of Science Education, 28(9), 957–976. https://doi.org/10.1080/09500690600702470

Girmay, S., Schönach, P., Wilson, B. P., Karttunen, A. J., & Yliniemi, K. (2026). Nondigital game creation as a teaching method for sustainability of nanomaterials: Student view to learning and the role of emotions. Journal of Chemical Education, 103(4), 1779–1792. https://doi.org/10.1021/acs.jchemed.5c01241

Godin, E. A., Wormington, S. V., Perez, T., Barger, M. M., Snyder, K. E., Richman, L. S., Schwartz-Bloom, R., & Linnenbrink-Garcia, L. (2015). A pharmacology-based enrichment program for undergraduates promotes interest in science. CBE—Life Sciences Education, 14(4), ar40. https://doi.org/10.1187/cbe.15-02-0043

Goes, L. F., Fernandez, C., & Eilks, I. (2020). The development of pedagogical content knowledge about teaching redox reactions in German chemistry teacher education. Education Sciences, 10(7), 170. https://doi.org/10.3390/educsci10070170

Graulich, N., Atkinson, M., Bernholt, S., Bhattacharyya, G., Lewis, S. E., Popova, M., Shultz, G. V., Stowe, R., & Pölloth, B. (2026). Myths about teaching and learning organic chemistry. Journal of Chemical Education, 103(3), 1145–1158. https://doi.org/10.1021/acs.jchemed.5c01507

Guzel, H., & Coskun, S. (2013). Effect of multiple intelligence theory-based profiles of technical vocational high school students on their success. Energy Education Science and Technology Part B: Social and Educational Studies, 5(1), 363–372.

Hermanns, M., Lilly, M. L., Wilson, K., & Russell, N. A. (2012). Name that neurotransmitter: Using music to teach psychopharmacology concepts. Journal of Nursing Education, 51(9), 517–520. https://doi.org/10.3928/01484834-20120730-01

Houseknecht, J. B., Bachinski, G. J., Miller, M. H., White, S. A., & Andrews, D. M. (2020). Effectiveness of the active learning in organic chemistry faculty development workshops. Chemistry Education Research and Practice, 21(1), 387–398. https://doi.org/10.1039/c9rp00137a

Huang, J. (2020). Successes and challenges: Online teaching and learning of chemistry in higher education in China in the time of COVID-19. Journal of Chemical Education, 97(9), 2810–2814. https://doi.org/10.1021/acs.jchemed.0c00671

Hundertmark, J., Alvarez, S., Loukanova, S., & Schultz, J.-H. (2019). Stress and stressors of medical student near-peer tutors during courses: A psychophysiological mixed methods study. BMC Medical Education, 19(1), 95. https://doi.org/10.1186/s12909-019-1521-2

Jang, H. Y., & Kim, H. J. (2020). A meta-analysis of the cognitive, affective, and interpersonal outcomes of flipped classrooms in higher education. Education Sciences, 10(4), 115. https://doi.org/10.3390/educsci10040115

Johnstone, A. H. (1991). Why is science difficult to learn? Things are seldom what they seem. Journal of Computer Assisted Learning, 7(2), 75–83. https://doi.org/10.1111/j.1365-2729.1991.tb00230.x

Kelley, E. W. (2021). LAB theory, HLAB pedagogy, and review of laboratory learning in chemistry during the COVID-19 pandemic. Journal of Chemical Education, 98(8), 2496–2517. https://doi.org/10.1021/acs.jchemed.1c00457

Kibga, E. S., Gakuba, E., & Sentongo, J. (2021). Developing students' curiosity through chemistry hands-on activities: A case of selected community secondary schools in Dar es Salaam, Tanzania. Eurasia Journal of Mathematics, Science and Technology Education, 17(5), em1962. https://doi.org/10.29333/ejmste/10856

Lang, F. K., Randles, C. A., & Jeffery, K. A. (2020). Developing and evaluating a graduate student teaching assistant training course in the chemistry department of a large research university. Journal of Chemical Education, 97(6), 1515–1529. https://doi.org/10.1021/acs.jchemed.9b00686

Llanos, J., Fernández-Marchante, C. M., García-Vargas, J. M., Lacasa, E., De La Osa, A. R., Sanchez-Silva, M. L., De Lucas-Consuegra, A., Garcia, M. T., & Borreguero, A. M. (2021). Game-based learning and just-in-time teaching to address misconceptions and improve safety and learning in laboratory activities. Journal of Chemical Education, 98(10), 3118–3130. https://doi.org/10.1021/acs.jchemed.0c00878

Marcelino, L. V., Dias, E. D. S., Rüntzel, P. L., Milli, J. C. L., Santos, J. S., Souza, L. C. A. B., & Marques, C. A. (2023). Didactic features specific to green chemistry teaching in the Journal of Chemical Education. Journal of Chemical Education, 100(7), 2529–2538. https://doi.org/10.1021/acs.jchemed.2c01091

Markovnikova, A. I., Likhanov, M. V., & Kurushkin, M. V. (2024). A model for estimating the visual complexity of a molecule using graph theory metrics: An educational perspective. Perspektivy Nauki i Obrazovania, 69(3), 602–620. https://doi.org/10.32744/pse.2024.3.37

Mei, Y., & Yang, B. (2017). Using Vincent van Gogh's illnesses to revise medicinal chemistry. Indian Journal of Pharmaceutical Education and Research, 51(1), 9–13. https://doi.org/10.5530/ijper.51.1.2

Mutambuki, J. M., Mwavita, M., Muteti, C. Z., Jacob, B. I., & Mohanty, S. (2020). Metacognition and active learning combination reveals better performance on cognitively demanding general chemistry concepts. Journal of Chemical Education, 97(7), 1832–1840. https://doi.org/10.1021/acs.jchemed.0c00254

Nezhyva, M., Aerts, J. T., Sandbaumhüter, F. A., Vallianatou, T., & Jansson, E. T. (2024). Inquiry-based learning of proteomics and metabolomics. Journal of Chemical Education, 101(2), 521–529. https://doi.org/10.1021/acs.jchemed.3c01041

Oztay, E. S., & Boz, Y. (2022). Interaction between pre-service chemistry teachers' pedagogical content knowledge and content knowledge in electrochemistry. Journal of Pedagogical Research, 6(1), 245–269. https://doi.org/10.33902/JPR.2022.165

Pagliaro, M. (2019). Chemistry education fostering creativity in the digital era. Israel Journal of Chemistry, 59(6), 565–571. https://doi.org/10.1002/ijch.201800179

Rahmawati, Y., Taylor, E., Taylor, P. C., Ridwan, A., & Mardiah, A. (2022). Students' engagement in education as sustainability: Implementing an ethical dilemma–STEAM teaching model in chemistry learning. Sustainability, 14(6), 3554. https://doi.org/10.3390/su14063554

Schmidt, S. J. (2020). Exploring the influence of course elements and emotional connection to content on students' approaches to learning in an introductory food science and human nutrition course. Journal of Food Science Education, 19(2), 59–73. https://doi.org/10.1111/1541-4329.12180

Seery, M. K. (2015). Flipped learning in higher education chemistry: Emerging trends and potential directions. Chemistry Education Research and Practice, 16(4), 758–768. https://doi.org/10.1039/C5RP00136F

Sevian, H., & Talanquer, V. (2014). Rethinking chemistry: A learning progression on chemical thinking. Chemistry Education Research and Practice, 15(1), 10–23. https://doi.org/10.1039/C3RP00111C

Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. Educational Researcher, 15(2), 4–14. https://doi.org/10.3102/0013189X015002004

Stephenson, N. S., Miller, I. R., & Sadler-McKnight, N. P. (2019). Impact of peer-led team learning and the science writing and workshop template on the critical thinking skills of first-year chemistry students. Journal of Chemical Education, 96(5), 841–849. https://doi.org/10.1021/acs.jchemed.8b00836

Sunday, O. J., Oni, O. S., & Fabiyi, D. (2026). The predictive influence of concept maps, prior knowledge, and motivational variables on chemistry learning outcomes. School Science and Mathematics. https://doi.org/10.1111/ssm.70012

Talanquer, V. (2011). Macro, submicro, and symbolic: The many faces of the chemistry "triplet." International Journal of Science Education, 33(2), 179–195. https://doi.org/10.1080/09500690903386435

Treagust, D. F., Qureshi, S. S., Vishnumolakala, V. R., Ojeil, J., Mocerino, M., & Southam, D. C. (2020). Process-oriented guided inquiry learning (POGIL) as a culturally relevant pedagogy in Qatar. Research in Science Education, 50(3), 813–831. https://doi.org/10.1007/s11165-018-9712-0

Valdez, J. E., & Bungihan, M. E. (2019). Problem-based learning approach enhances the problem-solving skills in chemistry of high school students. Journal of Technology and Science Education, 9(3), 282–294. https://doi.org/10.3926/jotse.631

van Eck, N. J., & Waltman, L. (2010). Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics, 84(2), 523–538. https://doi.org/10.1007/s11192-009-0146-3

Vincent-Ruz, P., Meyer, T., Roe, S. G., & Schunn, C. D. (2020). Short-term and long-term effects of POGIL in a large-enrollment general chemistry course. Journal of Chemical Education, 97(5), 1228–1238. https://doi.org/10.1021/acs.jchemed.9b01052

Vivas-Reyes, R., Navarro, D., & Cortes, L. E. (2024). Exploring emergent properties in chemistry education: A philosophical perspective on the molecular revolution. Journal of Chemical Education, 101(10), 4173–4181. https://doi.org/10.1021/acs.jchemed.4c00238

Vogelzang, J., Admiraal, W. F., & van Driel, J. H. (2019). Scrum methodology as an effective scaffold to promote students' learning and motivation in context-based secondary chemistry education. Eurasia Journal of Mathematics, Science and Technology Education, 15(12), em1783. https://doi.org/10.29333/ejmste/109941

Vogelzang, J., Admiraal, W. F., & van Driel, J. H. (2020). Effects of Scrum methodology on students' critical scientific literacy: The case of green chemistry in secondary schools. Chemistry Education Research and Practice, 21(3), 940–952. https://doi.org/10.1039/d0rp00066c

Widyasari, F., Masykuri, M., Mahardiani, L., Saputro, S., & Yamtinah, S. (2022). Measuring the effect of subject-specific pedagogy on TPACK through the flipped classroom of pre-service chemistry teachers. International Journal of Instruction, 15(3), 1007–1030. https://doi.org/10.29333/iji.2022.15354a

Wilczek, L. A., Clarke, A. J., Del Carmen Guerrero, M., & Gardner, S. M. (2022). Catalyzing the development of self-efficacy and science identity in an undergraduate chemistry research experience. Journal of Chemical Education, 99(12), 3878–3887. https://doi.org/10.1021/acs.jchemed.2c00352

Yoder, R. J., Bobbitt-Zeher, D., & Sawicki, V. (2021). Understanding the use of student-centered teaching methods in undergraduate chemistry courses. Research in Science Education, 51(3), 845–863. https://doi.org/10.1007/s11165-019-9820-5

Zimmermann, F., Melle, I., & Huwer, J. (2021). Developing prospective chemistry teachers' TPACK—A comparison between students of two different universities and expertise levels. Journal of Chemical Education, 98(6), 1863–1874. https://doi.org/10.1021/acs.jchemed.0c01296

Zupic, I., & Čater, T. (2015). Bibliometric methods in management and organization. Organizational Research Methods, 18(3), 429–472. https://doi.org/10.1177/1094428114562629