

Inquiry-Based Learning in STEM Education: A Scientometric Mapping of Research Trends, Hotspots, and Future Directions

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ABSTRACT

Inquiry-based learning (IBL) has emerged as a cornerstone of innovative STEM education, fostering student agency and scientific thinking. However, the field remains fragmented, with limited synthesis of its evolving intellectual foundations and thematic directions. The present study employed a comprehensive bibliometric analysis to map the global landscape of IBL research within STEM education published between 1997 and July 2025. Drawing on 1,048 documents retrieved from the Scopus database, the study analyzed performance indicators, co-citation networks, and keyword co-occurrence patterns using VOSviewer. Results revealed a consistent rise in scholarly output and citations, reflecting a growing recognition of IBL's pedagogical value. Four major intellectual clusters were identified, which emphasize curriculum standards, inquiry-driven reforms, cognitive learning perspectives, and evidence-based teaching practices. Co-word analysis revealed emergent themes, such as digital learning integration, pedagogical innovation, and disciplinary adaptation across science and engineering education. Critically, this study provides a structured lens for educators, policymakers, and researchers to navigate the complex terrain of IBL in STEM, offering empirical insights into prevailing discourses and knowledge gaps. The findings place emphasis on the need for deeper transdisciplinary collaboration, localized pedagogical models, and inquiry-based frameworks that respond to the demands of 21st-century learning. As STEM education continues to evolve, this study serves as a conceptual roadmap for future scholarship and policy-making grounded in evidence-based inquiry.

KEY WORDS: Bibliometric analysis, Co-citation, Co-word analysis, Inquiry-based learning, Science mapping, STEM education

INTRODUCTION

The 21st century is marked by accelerating scientific and technological transformations that demand equally innovative educational responses. In particular, STEM education must equip learners with the capacity to think critically, solve complex problems, and engage in authentic inquiry. Inquiry-based learning (IBL) has emerged as a potent pedagogical model aligned with these goals, emphasizing student-centered exploration, questioning, and evidence-based reasoning (Hmelo-Silver et al., 2007; Pedaste et al., 2015). Rooted in the constructivist theories of Piaget (1972) and Vygotsky (1978), IBL encourages active knowledge construction through experience and social interaction, making it especially relevant in today's rapidly evolving knowledge economies.

Empirical research consistently demonstrates the effectiveness of IBL in promoting deeper conceptual understanding, scientific literacy, and the development of higher-order cognitive skills, which are competencies that are vital in addressing contemporary global challenges (Bybee, 2013; Sam, 2024; Kotsis, 2024). Beyond cognitive outcomes, IBL has been shown to improve students' motivation, engagement, and STEM career interest, while also helping to close gender gaps in science learning (Ribeirinha et al., 2024; Teplá and Distler, 2025). Consequently, educational reform frameworks

led by organizations, such as the OECD and UNESCO have strongly endorsed the integration of IBL into both K–12 and higher education curricula (OECD, 2016; UNESCO, 2017).

Despite its increasing prominence, the IBL research landscape within STEM education remains fragmented and conceptually diffused. IBL has been implemented across a spectrum, from structured and guided inquiry to open-ended investigation, and adapted across disciplines, digital modalities, and learner levels (Bell et al., 2005; Antonio and Prudente, 2021; Sadeh and Zion 2012). This diversity has enriched the field but also led to a proliferation of subdomains, making it difficult to discern its intellectual structure, trace its evolution, or identify coherent research trajectories. While several systematic reviews and meta-analyses have evaluated the impact of IBL on academic outcomes (Lazonder and Harmsen, 2016; Schroeder et al., 2007; Antonio and Prudente, 2024), few have attempted to map the broader contours of IBL research through a macro-level, data-driven lens, particularly within the interdisciplinary domain of STEM education.

Bibliometric analysis presents a rigorous and scalable methodology for addressing this gap. By systematically analyzing large-scale bibliographic data, bibliometrics reveals patterns in scholarly production, influential publications and authors, research collaboration networks, and thematic trends (Donthu et al., 2021; Zupic and Čater, 2015). Unlike traditional

reviews that often rely on manual synthesis and selective sampling, bibliometric approaches provide a quantitative and visual mapping of the field's development over time. In the context of IBL, only a few fragmented bibliometric efforts have been undertaken, often limited to specific domains, such as elementary science or online biology education (Awinda and Mahendra, 2024; Lismaya et al., 2024). None, however, has provided a comprehensive, longitudinal analysis of the IBL research landscape across the broader STEM education spectrum.

To address this critical research gap, the present study conducts a comprehensive bibliometric and science-mapping analysis of global literature on IBL within STEM education. Utilizing the advanced bibliometric tool VOSviewer, the study systematically examines the historical development and publication trajectory of IBL research in STEM contexts. It further explores the intellectual and conceptual structure of the field, uncovers patterns of collaboration among authors, institutions, and countries, and identifies emerging thematic clusters and future research directions. Across this macro-level synthesis, the study provides a data-driven foundation for shaping future research agendas, informing policy decisions, and guiding pedagogical innovation. By mapping the evolution and structure of IBL scholarship, this work advances the global discourse on inquiry-based, evidence-informed STEM education, ensuring its responsiveness to the demands of an increasingly dynamic and interconnected world.

LITERATURE REVIEW

IBL in STEM Education

IBL is grounded in constructivist learning theories, particularly the seminal works of Piaget (1972) and Vygotsky (1978), which emphasize learners' active role in constructing knowledge through experience, exploration, and social interaction. Within STEM education, IBL represents a fundamental shift from traditional teacher-centered instruction toward learner-driven approaches that promote questioning, investigation, and evidence-based reasoning (Lower-Hoppe et al., 2021). This pedagogical orientation positions students not as passive recipients of information but as active participants in the knowledge-building process.

Extensive empirical research has established IBL as an effective approach for fostering scientific literacy, critical thinking, and problem-solving skills, which are competencies that are increasingly vital in an information-rich and technologically advanced society (Kotsis, 2024; NRC, 2012; Sam, 2024). These outcomes align closely with the goals of integrated STEM education, which emphasizes interdisciplinary learning and the application of knowledge to authentic, real-world contexts. Consequently, IBL has been widely adopted across educational levels, from primary classrooms to undergraduate science laboratories, as a means of creating more engaging and meaningful STEM learning environments (Krajcik and Blumenfeld, 2006; Marshall and Horton, 2011).

Beyond its recognition as an innovative pedagogical approach, IBL provides a coherent instructional architecture for integrating the core disciplines of STEM—Science, Technology, Engineering, and Mathematics. At its theoretical core, IBL operationalizes constructivist and socio-constructivist principles by engaging learners in authentic scientific practices, purposeful use of technological tools, engineering design processes, and mathematical reasoning within unified learning experiences. Rather than treating STEM disciplines as isolated domains, IBL fosters interdisciplinary sense-making by anchoring learning in real-world problems that require students to generate questions (science), collect and analyze data using digital tools (technology), design and test solutions through iterative processes (engineering), and apply quantitative reasoning and modeling (mathematics). In this sense, IBL functions as a pedagogical integrator that aligns disciplinary knowledge with crosscutting practices and epistemic goals, consistent with the holistic vision of STEM education articulated in contemporary curriculum frameworks, such as the Framework for K–12 Science Education and the Next Generation Science Standards (NGSS).

In practice, IBL manifests along a continuum of instructional guidance, ranging from structured inquiry—where teachers define the research questions and procedures—to open inquiry, in which students independently design and conduct investigations. Guided inquiry, situated between these two extremes, has been shown to be particularly effective in STEM disciplines because it balances learner autonomy with appropriate instructional scaffolding (Bell et al., 2005; Furtak et al., 2012). Various inquiry-oriented strategies have emerged within this continuum, including process-oriented guided inquiry learning and argument-driven inquiry, both of which have demonstrated effectiveness in developing science process skills and deepening conceptual understanding (Antonio and Prudente, 2021; Purtadi et al., 2023). Recent innovations have further extended IBL through the integration of digital technologies, gamified learning environments, and socio-scientific issues, enhancing its relevance and adaptability in 21st-century STEM education (Zacharia et al., 2015).

Importantly, the different levels of inquiry are closely associated with distinct STEM disciplinary components and learning practices. Structured inquiry aligns most strongly with scientific investigation in science education, where students engage with teacher-defined questions and procedures to develop foundational science process skills, such as observation, data collection, and evidence-based explanation. Guided inquiry serves as a bridge across science, technology, and mathematics by enabling learners to investigate teacher-posed problems while independently selecting analytical tools, digital technologies, and quantitative representations, thereby fostering data literacy, modeling, and computational reasoning. Open inquiry, characterized by student-generated questions and self-directed investigation, aligns most closely with engineering education and design-based STEM learning, as learners engage in iterative cycles of problem definition,

solution prototyping, testing, and optimization. In this context, open inquiry closely mirrors the engineering design process, requiring the integrated application of scientific principles, technological tools, and mathematical reasoning to develop and refine solutions to authentic problems. Collectively, these inquiry levels highlight IBL not as a uniform instructional method but as a flexible pedagogical continuum capable of supporting differentiated and context-sensitive STEM integration across disciplines and learning goals.

Empirical Evidence on the Impact of IBL in STEM Education

IBL significantly improves student outcomes in STEM education, particularly conceptual understanding, critical thinking, and higher-order cognitive skills (Antonio and Prudente, 2024; Mediana et al., 2025). Recent meta-analyses highlight moderate-to-large effects of IBL on learners' analytical and problem-solving capabilities, emphasizing the importance of structured facilitation and technology integration (Arifin et al., 2025). Beyond cognitive outcomes, IBL enhances student motivation, attitudes, and engagement in STEM, fostering increased career interest and addressing gender disparities by boosting self-efficacy, especially among female students (Teplá and Distler, 2025; Ribeirinha et al., 2024). However, implementation challenges, such as time management, inadequate teacher training, insufficient materials, and assessment pressures persist (Nicol, 2021; Gutierrez, 2015). Addressing these through sustained professional development and collaborative instructional strategies, such as lesson study and project-based learning remains essential for effective IBL practice (Odell and Kennedy, 2020; Sam, 2024).

Existing Reviews and Gaps in Synthesizing IBL Research

Recent bibliometric analyses have explored IBL trends across diverse educational contexts, offering valuable yet fragmented insights. In elementary science education, Awinda and Mahendra (2024) observed that IBL research has received limited international attention, with recurring keywords, such as “inquiry-based learning,” “students,” and “elementary school” reflecting its concentrated focus. Similarly, in the context of biology online education, Lismaya et al. (2024) identified critical thinking and problem-solving as dominant aspects of higher-order thinking, with interactive digital content emerging as the most frequently used instructional medium. In the domain of digital IBL, Ramli and Borhan (2024) mapped distinct thematic clusters centered on digital tool integration, student engagement, and learning outcomes, highlighting a growing trend in technologically supported inquiry. Meanwhile, in primary education, Wulandari et al. (2025) emphasized that IBL remains a favored pedagogical model, as evidenced by the prevalence of keywords, such as “reading dialogue,” “science education,” and “primary education.” Collectively, these studies highlight the continuing relevance of IBL and its adaptability across instructional levels, subject areas, and delivery formats.

Despite the growing academic interest, bibliometric analyses exclusively focusing on IBL remain relatively scarce and

limited in scope. Many existing studies treat IBL as a subset within broader pedagogical or disciplinary trends, rather than examining it as a distinct field of inquiry. While prior research offers important snapshots of IBL's application and thematic focus, it often lacks a comprehensive, macro-level perspective on how IBL scholarship has evolved over time, particularly within the STEM education domain. Key questions remain underexplored: How has the volume and thematic composition of IBL research changed across decades? Which countries, institutions, and authors are leading contributions? What are the dominant patterns of collaboration, and which emerging themes are shaping future directions?

Addressing these questions necessitates a rigorous bibliometric and scientometric approach. Unlike traditional reviews or meta-analyses, bibliometric analysis provides a data-driven, longitudinal overview of research trends, intellectual structures, and knowledge diffusion patterns. Applying such a method to IBL in STEM education can yield a more holistic understanding of the field's development, uncover influential works and networks, and guide scholars, educators, and policymakers in identifying research gaps and future priorities.

The present study addresses this critical research gap by offering a comprehensive bibliometric and science mapping analysis of literature on IBL in STEM education. Unlike previous reviews, this study captures the interdisciplinary, temporal, and structural characteristics of the IBL-STEM research landscape using advanced bibliometric tools, such as VOSviewer and Biblioshiny. By analyzing publication trends, collaboration networks, prolific contributors, core journals, and thematic clusters, the study provides novel insights into the growth, focus, and direction of IBL scholarship in STEM contexts. This macro-level perspective is crucial for guiding future research, informing policy decisions, and supporting evidence-based practices in STEM teaching and learning.

METHODOLOGY

Bibliometric Approach

This study employed a bibliometric research design to systematically map and analyze the intellectual, conceptual, and social structures of scholarship on IBL in STEM education. Bibliometric methods are particularly effective for examining the development of research fields that are interdisciplinary and pedagogically complex, such as IBL, which spans science education, cognitive psychology, curriculum studies, and technology-enhanced learning (Donthu et al., 2021; Zupic and Čater, 2015). In contrast to narrative or systematic reviews, which rely heavily on qualitative interpretation, bibliometric analysis uses quantitative indicators to uncover publication trends, citation impact, thematic structures, and scholarly networks (Hemmingsen et al., 2023). By visualizing and quantifying knowledge production, this approach provides a robust lens through which to assess how inquiry-based pedagogies are evolving within STEM education.

More specifically, the study adopted the bibliometric workflow proposed by Aria and Cuccurullo (2017), which includes: (1) Data retrieval, (2) data cleaning and preparation, (3) performance and network analysis, and (4) visualization using science mapping techniques. VOSviewer was used for generating co-citation networks, keyword co-occurrence maps, and authorship linkages.

Search Strategy and String

Data were retrieved from the Scopus database due to its broad coverage of peer-reviewed and non-peer-reviewed literature, including journal articles, books, book chapters, and conference proceedings (Baas et al., 2020). To ensure the retrieval of literature relevant to IBL in the context of STEM education, a well-defined search string was used, guided by Boolean logic and expert-informed keyword selection.

The following query was applied to the TITLE-ABS-KEY fields in the Scopus database: (“inquiry-based learning” OR “inquiry learning” OR “inquiry-based teaching”) AND (“STEM education” OR “science education” OR “engineering education” OR “mathematics education” OR “technology education”). This search string captured studies that explicitly addressed the implementation, evaluation, or conceptual framing of inquiry-based pedagogies across the STEM domains. No restrictions were placed on publication year, document type, or source type to ensure a comprehensive and longitudinal view of the research landscape. The dataset includes publications indexed up to July 2025, which corresponds to the month when the Scopus data were retrieved; therefore, publications appearing after this date were not included in the analysis.

Inclusion and Exclusion Criteria

To ensure the relevance, quality, and rigor of the analysis, a set of clearly defined inclusion and exclusion criteria was applied during the data selection process. Documents were included if they explicitly discussed IBL or teaching as a core concept and were situated within the domains of science, technology, engineering, or mathematics (STEM) education. Only publications indexed in the Scopus database were considered, and all included works were required to be written in English and contain relevant content in their titles, abstracts, or keywords. Eligible document types encompassed peer-reviewed journal articles, conference papers, books, book chapters, and other scholarly outputs. Conversely, documents were excluded if they were published in languages other than English, lacked bibliographic completeness (such as missing author or title information), or referenced IBL only in passing without educational or pedagogical relevance. Editorials, errata, and non-scholarly commentaries were also excluded. These criteria were established to curate a focused and academically robust dataset that accurately reflects meaningful contributions to the evolving discourse on IBL within STEM education.

Data Cleaning and Preparation

After retrieving the dataset from Scopus, records were exported in CSV formats, including fields, such as title, authors,

affiliations, publication source, year, abstract, keywords, and citation counts. The dataset underwent a thorough data cleaning process to ensure analytical reliability. The cleaned dataset was then uploaded to VOSviewer, where co-authorship networks, co-citation maps, and co-occurrence keyword clusters were generated to uncover patterns of collaboration, influence, and conceptual convergence.

Analytical Techniques

The study employed a dual analytical approach combining performance analysis and science mapping to examine the bibliometric dataset. Performance analysis was used to assess publication productivity across years, sources, authors, institutions, and countries, as well as citation performance to identify influential documents and contributors. Science mapping techniques were applied to reveal the intellectual and conceptual structure of the IBL-STEM research landscape. Specifically, co-citation analysis was conducted to identify foundational works and theoretical linkages that constitute the field’s intellectual core, while co-word (keyword co-occurrence) analysis was used to map dominant research themes, conceptual clusters, and thematic relationships. Collectively, these analytical techniques provided a multi-dimensional understanding of research trends, influence patterns, and thematic developments in IBL within STEM education.

FINDINGS

Descriptive Analysis of Publication Trends and Research Productivity in IBL in STEM Education

The bibliometric search conducted in the Scopus database yielded a comprehensive corpus of 1,048 documents related to IBL in STEM education. Altogether, these documents have accrued a total of 24,860 citations, attesting to the increasing academic visibility and influence of IBL within the broader STEM education discourse. The h-index of 65 suggests that 65 publications have each been cited at least 65 times, reflecting both the productivity and citation impact of foundational studies in the field. The average number of citations per document stands at approximately 23.73, indicating a moderate yet sustained level of scholarly impact across the corpus. This metric highlights that while highly cited landmark papers exist, the overall influence is distributed across a broad range of publications, showcasing the field’s steady progression rather than dependency on a few seminal works.

As illustrated in Figure 1, the annual number of publications has shown a consistent upward trajectory, particularly notable from 2010 onward, coinciding with increased policy interest in STEM education reform and pedagogical innovation. The peak publication year was 2023, recording the highest volume of documents, followed by a slight decline in early 2025, likely due to the dataset’s cutoff period. A corresponding rise in citations mirrors the publication trend, with a marked surge between 2016 and 2023. This suggests a maturing research field characterized by increased academic attention, diversified

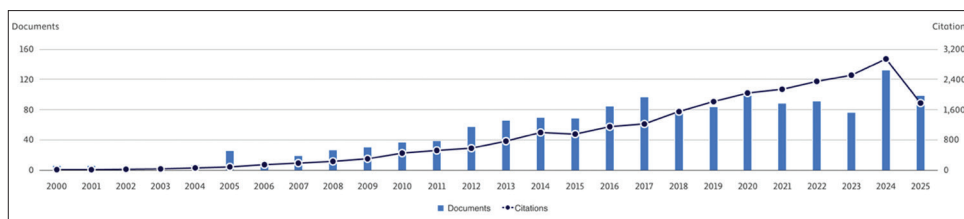


Figure 1: Annual publication and citation trends of Inquiry-based learning research in STEM education based on 1,048 Scopus-indexed documents

inquiry contexts, and intensified international collaboration. These descriptive metrics establish the foundational context for further analyses on the intellectual, conceptual, and collaborative structures of IBL research within STEM. The sustained growth in both publication volume and citation frequency signals the field’s relevance in addressing pressing educational demands and its potential for continued theoretical and pedagogical innovation.

Table 1 presents the global distribution of scholarly output on IBL in STEM education by highlighting the ten most productive countries. The United States dominates the field by a substantial margin, contributing nearly half of the total publications. This prominence reflects the long-standing emphasis on constructivist and student-centered pedagogies in U.S. educational reform, particularly following the implementation of the National Science Education Standards and the NGSS, both of which explicitly promote inquiry-oriented instruction.

Following the United States, countries, such as Germany, Australia, and China demonstrate strong research engagement, underscoring the international relevance of IBL as a pedagogical approach for advancing STEM education. The presence of Spain, Indonesia, Taiwan, and Thailand, representing diverse geographic regions and educational contexts, signals the growing internationalization and localization of inquiry-based frameworks, as nations adapt IBL to respond to their specific curricular priorities and sociocultural conditions.

Overall, this distribution suggests that while IBL research in STEM education is expanding globally, scholarly production remains uneven, with a concentration of output in the Global North. This imbalance highlights the need to further amplify research contributions from underrepresented regions, particularly in developing contexts where inquiry-based STEM education has significant potential to enhance scientific literacy, critical thinking, and problem-solving skills among learners.

Table 2 summarizes the top institutional affiliations contributing to research on IBL in STEM education. The results indicate a notable concentration of scholarly output within education-focused units, particularly at Khon Kaen University, Thailand, which accounts for four of the top five affiliations. The Science Education Program, Faculty of Education, Khon Kaen University, emerges as the most productive institution with ten publications, followed by the University of Twente, The Netherlands, with nine documents and substantially higher citation impact. While several Khon Kaen University units

Table 1: Top 10 Countries by number of publications on IBL research in STEM education

Rank	Country	Number of documents
1	United States	504
2	Germany	79
3	Australia	73
4	China	65
5	Spain	58
6	Indonesia	55
7	Netherlands	53
8	United Kingdom	48
9	Taiwan	46
10	Thailand	44

Source: Scopus data analyzed using VOSviewer. IBL: Inquiry-based learning

Table 2: Top institutional affiliations by number of publications on IBL in STEM education

Rank	Institution	Documents	Citations
1	Science Education Program, Faculty of Education, Khon Kaen University, Khon Kaen, Thailand	10	32
2	University of Twente, Enschede, The Netherlands	9	229
3	Institute of Learning and Teaching Innovation, Khon Kaen University, Khon Kaen, Thailand	6	18
4	Faculty of Education, Khon Kaen University, Khon Kaen, Thailand	6	7
5	Division of Science, Mathematics, and Technology Education, Faculty of Education, Khon Kaen University, Khon Kaen, Thailand	5	36
6	Graduate Institute of Applied Science and Technology, National Taiwan University of Science and Technology, Taipei, Taiwan	4	728
7	James Madison University, Harrisonburg, VA, United States	4	64
8	Westminster College, Salt Lake City, UT, United States	4	64
9	University of Sydney, Sydney, Australia	4	18
10	University of Nebraska–Lincoln, Lincoln, NE, United States	3	47

Source: Scopus data analyzed using VOSviewer. IBL: Inquiry-based learning

demonstrate strong publication productivity, institutions, such as the Graduate Institute of Applied Science and Technology,

National Taiwan University of Science and Technology, stand out in terms of citation influence, recording the highest citation count despite a smaller number of publications. Additional contributions from universities in the United States and Australia reflect the geographically diverse yet institutionally concentrated nature of IBL-STEM research. Overall, these findings suggest that a limited number of specialized education and STEM-focused institutions play a central role in advancing IBL scholarship.

Table 3 presents the most prolific authors in IBL research within STEM education. The findings show that Srisawasdi, Nivat, leads the field in publication output with 24 documents, indicating sustained scholarly productivity. This is followed by Panjaburee, Patcharin, de Jong, Ton, and Gillet, Denis, each contributing ten publications, while Pedaste, Margus, closely follows with nine documents. Although several authors demonstrate high publication volume, citation counts vary considerably across the top contributors. Notably, Tsai, Chin-Chung, and de Jong, Ton exhibit particularly high citation impact relative to their number of publications, reflecting strong scholarly influence within the IBL-STEM literature. Overall, the results indicate that a relatively small group of researchers accounts for a substantial share of both productivity and citation impact in the field.

As reflect in Figure 2, the pie chart presents the disciplinary distribution of publications on IBL in STEM education. Unsurprisingly, Social Sciences dominate the field, accounting for 42.0% of the total documents. This strong representation reflects the pedagogical and educational nature of IBL, emphasizing its foundational roots in learning theories, curriculum development, classroom practice, and teacher education, which are areas traditionally situated within the social sciences domain. Closely following are Engineering (14.3%) and Computer Science (16.8%), which highlight the expanding interest in integrating IBL approaches into technology-rich and application-oriented fields. In engineering education, IBL is often leveraged to foster design thinking, problem-solving, and innovation skills, aligning well with global demands for workforce-ready graduates. The

Table 3: Top 10 authors by number of publications on IBL in STEM education

Rank	Author	Documents	Citations
1	Srisawasdi, Nivat	24	87
2	Panjaburee, Patcharin	10	81
3	de Jong, Ton	10	510
4	Gillet, Denis	10	331
5	Pedaste, Margus	9	294
6	Ahmed, Sohaib	7	158
7	Douglas, Elliot P.	7	65
8	Slotta, James D.	6	305
9	Fischer, Frank	6	356
10	Tsai, Chin-Chung	6	822

Source: Scopus data processed using VOSviewer. IBL: Inquiry-based learning

prominence of computer science also suggests the rising influence of digital learning environments and computational thinking, particularly as educators explore ways to make coding, algorithms, and data literacy more inquiry-driven and student-centered. Other disciplines, such as Mathematics (6.3%), Psychology (4.2%), and Physics and Astronomy (3.5%) contribute more modestly, but importantly reflect the cross-disciplinary reach of IBL. Notably, the presence of Arts and Humanities, Agricultural Sciences, and Health Professions, though minimal, signals an emerging transdisciplinary interest in inquiry as a core instructional strategy beyond traditional STEM boundaries. In all, this distribution points to the multidisciplinary nature of IBL research while reaffirming its strongest theoretical and practical foothold in education and social science scholarship. The field would benefit from further integration across domains, especially those underrepresented, fostering interdisciplinary synergies that can enrich both the pedagogical applications and epistemological understandings of inquiry-based STEM education.

Citation Analysis and Scholarly Influence of IBL Research in STEM Education

Citation analysis serves as a cornerstone of bibliometric evaluation, providing insights into the scholarly influence and intellectual foundations of a research field. Table 4 presents the top ten most cited documents in the dataset, based on citation counts retrieved from Scopus. These landmark publications reflect the core conceptual, theoretical, and methodological contributions that have anchored and propelled the IBL-STEM research agenda.

As shown in Table 4, the most cited work is by Prince and Felder (2006), with 1,690 citations. While centered on inductive teaching methods, the paper positions IBL as a key learner-centered approach within engineering and science education, highlighting its foundational role in active learning frameworks. The second most cited article, by Schraw et al. (2006), with 859 citations, emphasizes the role of metacognition and self-regulation in science learning, framing IBL within a cognitive perspective that enhances conceptual understanding through reflective thinking. Edelson et al. (1999), ranked third with 663 citations, focuses on designing technology-supported inquiry environments, offering enduring strategies for aligning

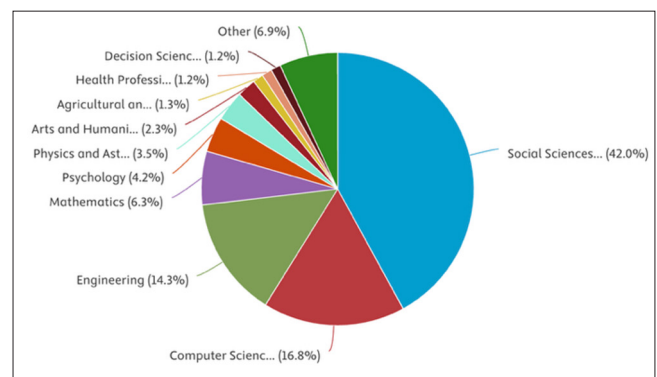


Figure 2: Number of documents by subject area (Source: Scopus)

Table 4: Top 10 most cited documents in IBL research within STEM education

Rank	Author (s)	Title	Journal	Citations
1	Prince and Felder (2006)	Inductive teaching and learning methods: Definitions, comparisons, and research bases	Journal of Engineering Education	1,690
2	Schraw et al. (2006)	Promoting self-regulation in science education: Metacognition as part of a broader perspective on learning	Research in Science Education	859
3	Edelson et al. (1999)	Addressing the challenges of inquiry-based learning through technology and curriculum design	Journal of the Learning Sciences	663
4	Ibáñez and Delgado-Kloos (2018)	Augmented reality for STEM learning: A systematic review	Computers and Education	662
5	Cheng and Tsai (2013)	Affordances of augmented reality in science learning: Suggestions for future research	Journal of Science Education and Technology	601
6	Sandoval (2005)	Understanding students' practical epistemologies and their influence on learning through inquiry	Science Education	536
7	Squire and Jan (2007)	Mad city mystery: Developing scientific argumentation skills with a place-based AR game	Journal of Science Education and Technology	392
8	Windschitl (2003)	Inquiry projects in science teacher education: Investigative experiences and teacher practice	Science Education	375
9	Bell et al. (2010)	Collaborative inquiry learning: Models, tools, and challenges	International Journal of Science Education	325
10	Eberlein et al. (2008)	Pedagogies of engagement in science: PBL, POGIL, and PLTL compared	Biochemistry and Molecular Biology Education	320

POGIL: Process-oriented guided inquiry learning. IBL: Inquiry-based learning

curriculum and pedagogy. Other highly cited works explore innovations, such as augmented reality (AR) in STEM (Ibáñez and Delgado-Kloos, 2018; Cheng and Tsai, 2013) and the development of scientific argumentation and epistemological thinking (Sandoval, 2005; Squire and Jan, 2007).

To gain deeper insights into the intellectual structure and evolving focus of IBL research in STEM education, the most frequently cited documents were examined for recurring conceptual patterns and contributions. These highly cited publications reveal three dominant and interrelated themes that characterize the field's current trajectory: (1) The integration of IBL within broader active and inductive teaching paradigms; (2) the convergence of IBL with emerging technologies to create immersive learning environments; and (3) the epistemic and cognitive dimensions of inquiry, including metacognition and scientific reasoning.

Theme 1: Integration of IBL with Active and Inductive Pedagogies

A dominant theme in the most influential literature is the positioning of IBL within the broader family of student-centered, inductive teaching methods. The highly cited work of Prince and Felder (2006) underscores how IBL aligns with pedagogies, such as problem-based learning (PBL), case-based learning, and project-based learning, all of which encourage learners to construct understanding through exploration and reflection. This integration reflects a paradigmatic shift in STEM education from passive knowledge transfer to active learning environments where inquiry drives the learning process. The theme emphasizes that IBL is not a standalone technique but a central pillar of broader instructional reform aimed at fostering critical thinking, deep understanding, and learner autonomy.

Theme 2: Technology-Enhanced Inquiry and the Rise of Immersive Learning Environments

Several top-cited studies (e.g., Ibáñez and Delgado-Kloos, 2018; Cheng and Tsai, 2013) highlight the increasing convergence of IBL with emerging digital technologies, particularly AR and mobile learning. These technologies offer dynamic, interactive, and context-rich platforms for conducting inquiry-based tasks, enabling students to visualize abstract concepts and manipulate virtual phenomena in STEM disciplines. The use of technology not only enhances engagement but also supports more authentic and situated forms of inquiry, aligning with the cognitive demands of scientific exploration. This theme illustrates the growing emphasis on designing digitally mediated IBL environments that are responsive to contemporary learners' needs and technological literacies.

Theme 3: Epistemic and Cognitive Dimensions of Inquiry Learning

Another core theme emerging from the literature is the focus on the epistemological and metacognitive foundations of inquiry learning. Works, such as those by Schraw et al. (2006) and Sandoval (2005) stress the importance of helping students not only engage in inquiry but also understand how knowledge is constructed, evaluated, and communicated. Metacognition, self-regulated learning, and scientific argumentation are central concepts in this theme. It highlights the role of IBL in developing students' disciplinary thinking and epistemic agency, enabling them to reason scientifically, justify claims with evidence, and reflect on their learning processes. This cognitive focus is crucial in preparing learners to tackle complex, real-world STEM problems.

These three themes collectively define the current trajectory and future direction of IBL research in STEM education. They

reflect that inquiry is not merely a method, but a transformative educational approach that blends theory, technology, and cognition to support meaningful learning in an increasingly complex world.

Co-Citation Analysis of the Intellectual Structure of IBL Research in STEM Education

Co-citation analysis offers a powerful lens to trace the intellectual structure of a research field by examining how frequently pairs of documents are cited together. Using VOSviewer, the present study analyzed 48,316 cited references and identified 51 core documents (threshold ≥ 11 citations) that are most frequently co-cited within the literature on IBL in STEM education. These documents form the backbone of the field's knowledge base, as their frequent joint citation signals their shared influence on ongoing academic conversations.

As shown in Table 5, the most prominent document by co-citation frequency is “National Science Education Standards” by AB (1996), with 151 citations and the highest total link strength of 313. This underscores the foundational role of policy frameworks in shaping inquiry-driven STEM education in the U.S. context. Closely following are the National Research Council's (2012) Framework for K–12 Science Education and NGSS (2013), both of which emphasize inquiry as a core scientific practice embedded within three-dimensional learning. These curricular and policy frameworks collectively define what students should know and be able to do, firmly positioning inquiry at the center of STEM teaching and learning.

Theoretical and empirical contributions are also highly co-cited. Kirschner et al. (2006) raised a provocative critique of unguided inquiry, prompting numerous scholarly responses (e.g., Hmelo-Silver et al., 2007) that defend scaffolded and structured inquiry. Meanwhile, Furtak et al. (2012) and Alfieri et al. (2011) contribute large-scale syntheses of IBL's effectiveness, reinforcing the empirical grounding of the field. These co-citation patterns indicate a well-established

intellectual network that bridges policy, theory, pedagogy, and evidence-based practice.

As shown in Figure 3, the co-citation network revealed four major thematic clusters that collectively define the intellectual structure of IBL in STEM education. Each cluster, represented by red, green, blue, and yellow nodes, reflects a distinct area of scholarly emphasis, from standards-driven reforms to theoretical lineages. The clustering illustrates how IBL is shaped by interlocking discourses in policy, pedagogy, research, and philosophy, offering a comprehensive lens into the development and current directions of the field.

Red Cluster: Policy and Curriculum Foundations of Inquiry

The red cluster is composed primarily of documents that have played a foundational role in shaping educational policy and curriculum standards related to inquiry. Central to this cluster are the National Science Education Standards (AB, 1996) and Inquiry and the National Science Education Standards (National Research Council [NRC], 2000), both of which emphasized the need for students to engage in inquiry not merely as a method but as a habit of scientific thinking. These were followed by the seminal Benchmarks for Science Literacy (AAAS, 1993), which provided performance-based goals that emphasized the role of inquiry in achieving scientific understanding.

Later developments, particularly the Framework for K–12 Science Education (NRC, 2012) and the NGSS (NGSS Lead States, 2013), elevated inquiry to the status of a core scientific practice, embedding it within the “three-dimensional learning” model that includes disciplinary content, crosscutting concepts, and science practices. These policy texts are not merely administrative documents—they anchor the field's normative commitments to inquiry-based pedagogy and represent the institutionalization of IBL at national and international levels.

The frequent co-citation of these documents demonstrates that IBL is not simply a classroom strategy, but a systemically endorsed principle of science education reform, aimed at aligning classroom learning with the epistemic practices of

Table 5: Top 10 most co-cited documents in IBL research and their total link strength

Author (s) and year	Document title	Citation	Total link strength
AB (1996)	National Science Education Standards	151	313
National Research Council (2012)	A Framework for K–12 Science Education	71	162
Kirschner et al. (2006)	Why Unguided Learning Does Not Work	47	144
NRC, Center for Science, Mathematics, Engineering Education (2000)	Inquiry and the National Science Education Standards	44	119
NGSS Lead States (2013)	Next Generation Science Standards: For States, by States	50	119
Anderson (2002)	Reforming Science Teaching: What Research Says About Inquiry	42	118
Hmelo-Silver et al. (2007)	Scaffolding and Achievement in Problem-Based and Inquiry Learning	24	86
Furtak et al. (2012)	Experimental and Quasi-Experimental Studies of Inquiry-Based Teaching	20	82
AAAS (1993)	Benchmarks for Science Literacy	37	81
Alfieri et al. (2011)	Does Discovery-Based Instruction Enhance Learning?	16	79

Source: Author interpretation based on VOSviewer analysis. IBL: Inquiry-based learning

between instructional design and teacher facilitation. This empirical strand of literature supports the transition of IBL from a theoretically appealing concept to a research-validated instructional practice adaptable to varied classroom contexts. Overall, this cluster affirms the centrality of practitioner expertise and evidence-informed decision-making in sustaining effective inquiry practices across STEM education systems.

Yellow Cluster: Pedagogical Lineages and Constructivist Traditions

The yellow cluster reflects the philosophical and theoretical foundations of IBL, tracing its roots to constructivist, experiential, and inductive learning paradigms. It includes canonical thinkers, such as Bruner (1961), who championed discovery learning as a process through which learners construct understanding by exploring and problem-solving. Likewise, Kolb's (1984) experiential learning theory emphasized learning as a cyclical process involving concrete experience, reflective observation, abstract conceptualization, and active experimentation. This cluster also includes work by Prince and Felder (2006), who situated IBL within the broader family of inductive teaching methods, including problem-based, project-based, and case-based learning. Their analysis provides an important bridge between constructivist learning theory and practical classroom strategies, helping to position IBL as part of a larger pedagogical ecosystem grounded in active and student-centered learning. The presence of these works in the co-citation network reveals how inquiry has not emerged in isolation but has been conceptually shaped by decades of educational theory, including those of Dewey (1938), who saw inquiry as central to democratic education and personal growth. This theoretical grounding gives IBL its epistemological legitimacy, reinforcing its relevance not only in science but across disciplines concerned with fostering autonomous, reflective learners.

In all, the four co-citation clusters offer a rich and multifaceted view of IBL in STEM education (Table 6). The red cluster legitimizes IBL through standards and policies, the green cluster refines its instructional design, the blue cluster demonstrates its empirical value and classroom realities, and the yellow cluster reconnects it to its philosophical roots. This clustering affirms that IBL is not a monolithic strategy but a conceptually layered and pragmatically adaptive framework, one that draws strength from both theory and practice, tradition and innovation.

The presence of four distinct yet interconnected clusters reveals that IBL in STEM education is not only a pedagogical approach but a rich, multi-faceted field of research and practice. Rooted in educational policy, shaped by theoretical debates, validated through empirical inquiry, and grounded in decades of pedagogical thought, IBL continues to evolve as a cornerstone of science education reform. The co-citation map illustrates the dynamic dialogue between policy, theory, practice, and philosophy, each contributing to a more nuanced and powerful understanding of how students learn through inquiry.

Co-Word Analysis of Research Themes and Conceptual Structure in IBL in STEM Education

To examine the semantic structure and thematic evolution of research on IBL in STEM education, a co-word analysis was performed using author keywords extracted from the bibliometric dataset. From a total of 5,507 unique keywords, 60 met the minimum threshold of 20 occurrences. Table 7 presents the 15 most frequently occurring keywords, led by students ($n = 455$), engineering education ($n = 425$), and inquiry-based teaching ($n = 476$). The keywords exhibit high total link strengths, indicating strong interconnectedness with other terms in the field. Notably, terms, such as inquiry learning, science education, curricula, and problem-solving reflect persistent pedagogical themes, while keywords, such as e-learning, education computing, and learning systems suggest the growing influence of digital environments in shaping inquiry-based pedagogies.

The resulting co-word network map (Figure 4) reveals four major thematic clusters, generated based on keyword co-

Table 6: Thematic co-citation clusters and representative publications in IBL research in STEM education

Cluster color	Thematic focus	Representative works
Red	Policy and Curriculum Foundations	AB (1996); NRC (2000; 2012); NGSS Lead States (2013); AAAS (1993)
Green	Instructional Design and Cognitive Scaffolding	Kirschner et al. (2006); Hmelo-Silver et al. (2007); Pedaste et al. (2015); Alfieri et al. (2011)
Blue	Evidence-Based Practice and Teacher Professional Learning	Anderson (2002); Furtak et al. (2012); Windschitl (2003); Crawford (2000); Bell et al. (2003)
Yellow	Pedagogical Lineages and Constructivist Traditions	Bruner (1961); Kolb (1984); Prince and Felder (2006); Dewey (1938); Osborne et al. (2003)

IBL: Inquiry-based learning

Table 7: Top 15 keywords identified in the co-occurrence network analysis

Rank	Keyword	Occurrences	Total link strength
1.	Students	455	2283
2.	Engineering education	425	2000
3.	Inquiry-based teaching	476	1655
4.	Teaching	287	1518
5.	Education	189	1018
6.	Curricula	181	1008
7.	Science education	288	710
8.	E-learning	106	604
9.	Education computing	102	593
10.	Computer-aided instruction	100	552
11.	Inquiry learning	164	536
12.	Learning systems	95	523
13.	Stem	53	326
14.	Active learning	67	301
15.	Problem-solving	51	295
16.	Professional aspects	43	272

environments, particularly in the wake of online and blended learning demands. This trend is supported by studies, such as Ibáñez and Delgado-Kloos (2018) and Cheng and Tsai (2013), who reviewed the role of augmented and virtual reality in supporting interactive and immersive inquiry in STEM education. Meanwhile, de Jong (2006) and Zacharia et al. (2015) emphasize the pedagogical affordances of simulations, virtual labs, and computer-supported collaborative learning environments. These tools not only offer scalability and personalization but also enhance students' ability to visualize abstract phenomena and engage in scientific modeling and experimentation. This cluster highlights a critical trajectory in IBL research, one where inquiry practices are being reconceptualized for 21st-century learning through technological innovation.

Green Cluster: Applied Inquiry in Engineering and STEM Contexts

Anchored by the high-frequency term engineering education ($n = 425$), this cluster points to the application of inquiry-based pedagogies in professional, vocational, and design-based STEM contexts. This includes inquiry as a mode of teaching and learning aligned with PBL, design challenges, and real-world scenarios in engineering and technical education.

Papers like Prince and Felder (2006) explore inductive learning strategies, including IBL, in engineering classrooms, while Squire and Jan (2007) and Edelson et al. (1999) illustrate how technology-rich, situated learning tasks can promote scientific argumentation and deeper content understanding. The inclusion of problem-solving in this cluster also reflects the goal of cultivating future-ready professionals who can engage with complex systems, collaborate in teams, and adaptively learn, which are skills essential in STEM careers.

This cluster suggests how inquiry learning is not limited to general education, but also functions as a professional preparation tool in engineering and applied sciences. It illustrates how IBL can foster the competencies needed to innovate and solve problems in authentic contexts. In essence, this cluster reflects the evolution of IBL into a tool for building real-world STEM capacities, particularly in disciplines, such as engineering, where design thinking and applied reasoning are key.

DISCUSSION

This bibliometric and science-mapping analysis offers a macro-level overview of the intellectual structure, thematic development, and scholarly influence of IBL in STEM education over the past two decades. The findings extend beyond publication trends to uncover ideological shifts, pedagogical tensions, and emerging research priorities. The evolution of IBL from a theoretical ideal to a dynamic, interdisciplinary discourse reflects its entrenchment in policy, technological advancement, and learner-centered imperatives.

A key theme evident in both co-citation and keyword analyses is the central role of policy-driven science education reforms in framing the IBL discourse. The prominence of documents, such as the National Science Education Standards (AB, 1996), the NGSS (NGSS Lead States, 2013), and the Framework for K–12 Science Education (NRC, 2012), points to the field's alignment with systemic curricular transformation. These frameworks institutionalize inquiry as central to teaching and learning, emphasizing scientific practices like questioning, explanation-building, and evidence-based argumentation. Their frequent co-citation highlights their foundational role in legitimizing IBL within formal education systems and informing teacher preparation (Anderson, 2002; Windschitl, 2003).

Despite broad endorsement, ongoing debates persist regarding the level of guidance required for effective inquiry. The high co-citation of Kirschner et al. (2006) reflects enduring concerns about cognitive load in minimally guided instruction. In contrast, counterarguments from scholars like Hmelo-Silver et al. (2007) have prompted a shift toward scaffolded or guided inquiry models. These approaches preserve student agency while recognizing the need for structured support, particularly for novice learners. This pedagogical tension has inspired empirical studies aimed at optimizing the balance between structure and autonomy (Furtak et al., 2012; Sandoval, 2005).

Another prominent trend is the integration of digital technologies into IBL. High-frequency terms, such as “e-learning” and “computer-aided instruction” point to the growing use of virtual tools to support inquiry-based teaching. Influential works in this area emphasize the potential of technologies like virtual and AR to enable immersive, hypothesis-driven exploration (Ibáñez and Delgado-Kloos, 2018; Cheng and Tsai, 2013). These tools help overcome logistical limitations of traditional laboratories while reinforcing core IBL elements, such as experimentation and collaborative problem-solving. This shift has gained urgency in light of the digital transformation of education and the expansion of remote learning.

The frequent occurrence of terms, such as “students,” “problem-solving,” and “active learning,” reinforces the field's shift toward cultivating learner agency and transferable competencies. Rather than serving as a method of content delivery, IBL is increasingly framed as a pathway for developing critical thinking, self-regulation, and collaboration (Schraw et al., 2006; Kotsis, 2024). The emphasis on learner development aligns with broader educational aims to prepare students for complex, real-world STEM challenges. Moreover, the appearance of “curricula” and “STEM” in co-occurrence patterns highlights efforts to embed inquiry into interdisciplinary and competency-based educational structures.

Although the four thematic clusters, mainly policy reform, instructional guidance, technological integration, and learner development, highlight distinct research directions, their intersections suggest an emerging integrative model of IBL. This model combines empirical grounding, digital innovation,

and student-centered learning. However, fragmentation remains. Engineering and physical sciences dominate the literature, while disciplines, such as environmental science and social science receive less attention. Similarly, few studies address culturally responsive inquiry, equity, or the decolonization of STEM instruction, despite the increasing importance of inclusive and context-sensitive pedagogy (Teplá and Distler, 2025; Ribeirinha et al., 2024).

Altogether, the findings suggest that future IBL research must move toward more inclusive, locally grounded, and equity-driven frameworks. Cross-cultural studies, indigenous knowledge integration, and alignment between global policy and grassroots practice are needed to sustain IBL's relevance and impact. In this way, bibliometric mapping is not merely a retrospective analysis but a forward-looking tool that charts pathways for a more equitable and inquiry-rich future in STEM education.

CONCLUSION

This bibliometric study provides a comprehensive synthesis of the evolving landscape of IBL in STEM education, drawing from 1,048 Scopus-indexed publications. The analysis reveals that IBL has developed into a globally relevant and interdisciplinary field, shaped by education reforms, digital innovation, and learner-centered pedagogies. Key thematic clusters, policy-driven standards, instructional guidance debates, technology-enhanced inquiry, and student competency development, reflect the field's complexity and dynamism. Despite these advances, the literature remains fragmented, with ongoing debates around scaffolding, underexplored STEM domains, and the need for more inclusive and context-sensitive inquiry models. Overall, this study maps critical developments and intellectual trajectories that can inform future research and practice. As STEM education continues to respond to technological and societal change, the sustained relevance of IBL will depend on its adaptability to diverse learners, digital modalities, and equity-driven frameworks.

Limitations and Future Research

While this bibliometric study offers a comprehensive overview of the IBL research landscape in STEM education, certain limitations should be acknowledged. The analysis was restricted to Scopus-indexed publications, potentially excluding relevant studies from other databases and non-English-language sources. Bibliometric indicators, such as citation counts and co-word co-occurrence are also time-sensitive and may not fully reflect the pedagogical value or contextual applicability of research. Moreover, the study's reliance on quantitative mapping techniques limits deeper insight into how IBL is enacted in practice. To address these gaps, future research should incorporate qualitative approaches, such as expert interviews or classroom-based case studies, and pursue longitudinal analyses across diverse cultural and disciplinary contexts. Investigations into the integration of IBL with emerging technologies and equity-

focused pedagogies are especially recommended to ensure its continued relevance and inclusiveness in evolving STEM learning environments.

Recommendations

Based on the findings of this bibliometric analysis, several directions are recommended to strengthen IBL in STEM education. Researchers are encouraged to move beyond simplistic debates on guided versus unguided inquiry by exploring context-sensitive and hybrid models that integrate scaffolding, metacognitive support, and student agency. As digital technologies increasingly mediate IBL, future studies should deepen investigations into the pedagogical and equity implications of tools, such as virtual reality, artificial intelligence, and data-rich learning environments. Localizing inquiry approaches by aligning them with learners' cultural contexts and community priorities is also vital, ensuring relevance and inclusivity. Moreover, sustained teacher professional development must be prioritized to build pedagogical capacity, reflective practice, and assessment literacy in IBL. Finally, equity should remain central to IBL's expansion, ensuring that students from marginalized, low-resource, and linguistically diverse backgrounds can access and benefit from inquiry-rich STEM experiences.

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