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Mapping the Paradigm Shift in Natural Science Education: A Structural Analysis of Problem-Based Learning and Socio-scientific Reasoning (2016–2026)

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Abstract

The escalating complexity of global socioscientific issues demands an urgent paradigm shift in natural science education toward frameworks that rigorously cultivate higher-order socioscientific reasoning. However, while problem-based learning (PBL) is widely applied, the literature remains fragmented, creating a pedagogical bottleneck that obscures clear pathways for structural instructional design. This study analyzes the research trajectory of critical thinking and PBL using a bibliometric analysis combined with a systematic literature review (SLR) based on the PRISMA protocol. Data from the Scopus database (2016–2026) yielded 99 eligible articles from an initial 433. The structural mapping reveals a paradigm shift from basic evaluation toward targeted problem-solving, with publications peaking in 2025 (29 articles) and driven prominently by contributors from the United States and Indonesia within core journals like Advances in Physiology Education. VOSviewer analysis identified three precise conceptual nodes: evidence-based pedagogical assessment, active learning implementation, and the conceptual nexus of PBL and critical thinking. The SLR synthesis indicates that PBL enhances these competencies specifically by scaffolding collaborative scientific inquiry and integrating blended active learning environments. Ultimately, these findings dictate that future instructional models must evolve beyond traditional boundaries, utilizing these structural nodes to design adaptive, technology-integrated curricula that effectively operationalize socioscientific reasoning.

Keywords: Active Learning, Critical Thinking, Higher-Order Thinking Skills, Scientific Inquiry, Vosviewer.

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INTRODUCTION

The escalating complexity of global challenges necessitates a paradigm shift in science education toward theoretical frameworks grounded in socioscientific reasoning (SSR) and futures thinking. Within this context, critical thinking skills transcend generic competencies; they are imperative for deconstructing scientific phenomena, analyzing complex information, evaluating empirical evidence, and making logical, data-driven decisions regarding socio-environmental issues.

However, conventional, teacher-cantered pedagogies frequently fail to cultivate these precise analytical and evaluative skills, often reducing science learning to passive rote memorization rather than active scientific inquiry. This structural failure creates a logical necessity for educational institutions to transition toward more active, student-centered learning models. One widely used approach is problem-based learning (PBL), as it is considered capable of enhancing higher-order thinking skills through investigation, discussion, and contextual problem-solving activities. Research by Styers *et al.,* (2018) shows that active learning can improve students' critical thinking skills in science learning. Furthermore, Amin et al. (2020) reported that PBL positively affects students' critical thinking abilities as well as their attitudes toward the environment. Furthermore, Amin *et al.*, (2020) reported that PBL positively affects students' critical thinking abilities as well as their attitudes toward the environment. Research by Liu & Pásztor, (2022) also confirms that PBL interventions are effective in enhancing critical thinking in higher education. Meanwhile, Sujatmika *et al.*, (2024) xplained that active and PBL models are effective strategies for developing higher-order thinking skills in science education. In addition to conventional learning, digital technology developments are also beginning to support the implementation of PBL through blended learning, virtual learning, and AI-assisted learning (Mohebbi *et al.*, 2022; Irawati & Sulisworo, 2023).

Although research on critical thinking and PBL in science education continues to grow, the current literature suffers from a significant instructional bottleneck that hinders cohesive curriculum development at the specific natural science education program level. A thematic synthesis of recent literature reveals that instead of addressing structural pedagogical gaps, much of the research remains heavily siloed; studies are predominantly confined to specific domains like health education or are evaluated merely through the subjective lens of student perceptions, rather than mapping comprehensive pedagogical developments (Latif et al., 2018; Matlala, 2021; De Silva et al., 2023; Karki et al., 2024). Concurrently, the field is experiencing a necessary paradigm shift marked by the emergence of multidisciplinary themes such as ethnoscience-PBL, computational thinking, and sustainability education (Verawati et al., 2025; Sukkamart et al., 2025). Rather than isolated trends, these constructs represent critical variables for modernizing science curricula to address urgent local socio-scientific issues—such as integrating disaster mitigation literacy and fostering 'Futures Thinking' to build environmental resilience. However, without a comprehensive bibliometric map to clarify the structural interrelationships of these emerging themes, their integration into higher-order science instruction remains theoretically ambiguous.

The rapid, unmapped diversification of these multidisciplinary themes creates an urgent mapping gap that traditional narrative reviews are ill-equipped to address, particularly given the post-2020 explosion of literature in this domain. Therefore, to properly evaluate this structural evolution, this study uses a bibliometric analysis approach combined with a systematic literature review (SLR). The justification for this method extends far beyond a generic capacity to handle large volumes of publication

data; rather, it leverages the essential structural and analytical power of network visualization to map exact keyword co-occurrences and identify future theoretical trajectories. Crucially, the validity of this macroscopic mapping is strictly anchored in the precision of the Boolean search logic utilized to systematically isolate the pedagogical intersections of PBL and critical thinking. Furthermore, integrating this structural mapping with an SLR allows the study to not only uncover the visual research network but also deeply synthesize specific empirical findings regarding the implementation of PBL and the enhancement of critical thinking skills in science education

Based on this background, this study aims to analyze the development of research on critical thinking and problem-based learning in science education using a bibliometric approach and a systematic literature review. The research questions in this study include: RQ1: How have publication trends on critical thinking and problem-based learning in science education evolved? RQ2: What are the dominant and emerging themes in research on critical thinking and problem-based learning in science education? RQ3: What is the conceptual structure and relationships between topics in critical thinking and problem-based learning research, and how can these structures practically inform the development of future instructional frameworks and science curriculum designs?

METHOD

This study used bibliometric analysis combined with a systematic literature review (SLR). The bibliometric approach was used to objectively and systematically map publication trends, collaboration networks, and the development of research themes, while the SLR was used to qualitatively synthesize relevant articles. To address the need for procedural transparency and exact replicability, this study adapted the PRISMA protocol by defining explicit technical parameters for database searches, multi-reviewer screening mechanics, and software thresholds.

The research data was obtained from the Scopus database, selected for its extensive international publication coverage and comprehensive article metadata. To ensure absolute reproducibility across the dynamic 2016–2026 timeframe, the data extraction was executed on May 15, 2026. The search string underwent an iterative refinement process to prevent system errors and bypass syntax limitations commonly encountered with raw queries in the Scopus engine. Following syntax validation, the final string was strictly applied to the "Article Title, Abstract, Keywords" (TITLE-ABS-KEY) fields using the following Boolean operators: TITLE-ABS-KEY(("critical thinking" OR "higher order thinking skills") AND ("problem-based learning" OR "PBL") AND ("science education" OR "science learning")). Narrower programmatic keywords—such as specific natural science education study program constraints—were intentionally excluded from this primary query. Maintaining this broader "science education" boundary ensured the comprehensive capture of holistic, multidisciplinary trends before subsequently evaluating their localized pedagogical

implications. All verified data yielding the 433 initial hits was then exported in CSV format for further analysis.

The article selection process followed the PRISMA steps, which include identification, screening, eligibility, and inclusion. This study followed a systematic procedure based on the PRISMA stages to ensure transparency, consistency, and methodological rigor, as illustrated in **Figure 1.**

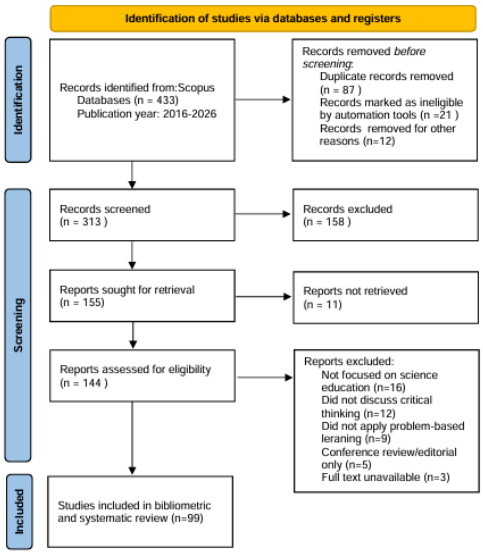


Figure 1. PRISMA flow diagram of the article selection process. Source: Developed by the authors based on PRISMA procedures and Scopus database search results.

During the identification phase, 433 articles were obtained from the Scopus database. To ensure rigorous human mechanics during the screening process, two independent reviewers evaluated the titles and abstracts, removing duplicate and irrelevant articles, which reduced the total number of articles to 313. The next stage, eligibility, was also carried out by these two independent reviewers, who selected full-text articles based on their relevance to the topic, abstract, content, and the explicitly established inclusion and exclusion criteria. Any disagreements between the reviewers regarding article eligibility were resolved through a consensus discussion; if a consensus could not be reached, a third senior reviewer intervened to make the final determination. After this rigorous final selection process, 99 articles fulfilled all the criteria and were used as the dataset for the bibliometric analysis and systematic synthesis.

This stage was used to ensure that the articles analyzed align with the research focus and meet the established inclusion and exclusion criteria, as shown in the table below.

Table 1. Inclusion and Exclusion Criteria

Inclusion Criteria	Exclusion Criteria
Articles discussing CT and PBL in the context of science education.	Studies that are not related to science education or do not specifically discuss critical thinking and PBL.

Inclusion Criteria	Exclusion Criteria
Articles focusing on the implementation, effectiveness, or development of critical thinking skills through PBL approaches in science learning.	Studies that only discuss general learning methods without relating them to critical thinking or PBL.
The document type is an original research article indexed in the Scopus database and has undergone a peer-review process.	Conference proceedings, book chapters, editorials, review notes, or non-scientific publications.
Articles published between 2016 and 2026.	Articles published outside the selected time range.
Articles containing empirical findings derived from robust research designs (e.g., quasi-experimental, longitudinal, or mixed-methods) that pass the Mixed Methods Appraisal Tool (MMAT) quality assessment threshold.	Conceptual papers, small-scale action research lacking comparative validity, or studies that fail the risk-of-bias evaluation.
Articles written in English and available in full-text form.	Articles that are inaccessible, incomplete, or only available as abstracts.

Next, data analysis was carried out using VOSviewer and Microsoft Excel. While alternatives such as CiteSpace or Biblioshiny offer distinct chronological mapping features, VOSviewer was specifically selected for its superior text-mining capabilities and modularity-based clustering algorithms, which are methodologically superior for untangling the complex, multidisciplinary keyword co-occurrences inherent in problem-based learning and critical thinking constructs. To ensure the resulting networks represent robust conceptual structures rather than random noise, specific threshold parameters were strictly applied: the minimum number of occurrences of a keyword was set to 5, resulting in 28 keywords meeting the threshold for inclusion in the final model. It is important to note a specific limitation encountered during the data extraction phase: a comprehensive VOSviewer thesaurus file was not entirely applied to merge all morphological variants (e.g., separating "student" and "students") or nested terminologies. While this resulted in the visualization of distinct synonymous nodes, post-extraction verification confirmed that this minor dilution did not alter the macro-thematic structural integrity of the generated clusters. Meanwhile, Microsoft Excel was used to analyze publication trends, productive countries, productive institutions, and key journals. The VOSviewer results were presented in the form of network visualization, overlay visualization, and density visualization to rigorously identify dominant themes, emerging topics, and research opportunities in CT and PBL research in science education.

RESULTS AND DISCUSSION

A. Performance Analysis
   1. Publication Trends

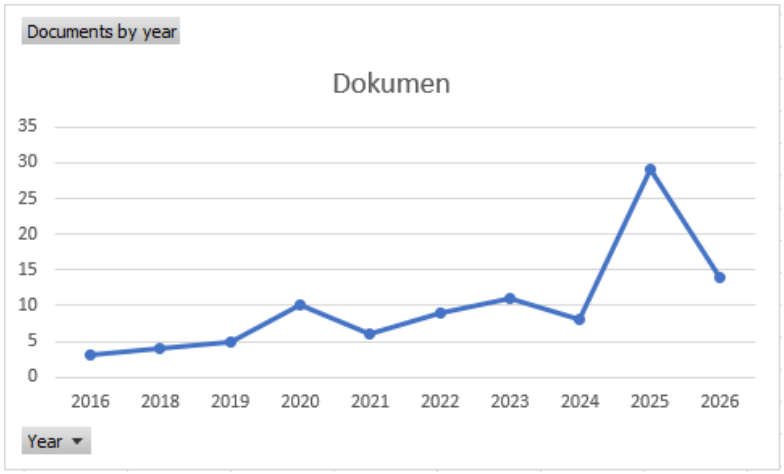


Figure 2. Distribution of annual publications on Critical Thinking and Problem-Based Learning in Science Education based on Scopus data for the period 2016-2026.

Publication trend analysis shows that this topic experienced fluctuating but generally increasing growth throughout the period 2016–2026.. In the initial phase, 2016–2019, the number of publications was relatively low and stable, indicating that the integration of CT and PBL was still in its early stages of development and had not yet become a primary focus in science education research.

Entering 2020, a significant increase occurred, signaling growing attention to the importance of critical thinking skills as part of 21st-century competencies. This trend continued, despite a temporary decline in 2021, generally attributed to global disruptions to education and research activities. However, in 2022–2023, the number of publications increased again, indicating a recovery and strengthening interest in the implementation of PBL in enhancing students' critical thinking abilities.

This development is inseparable from the shift in learning paradigms toward a more student-centered approach, as well as the increasing integration of technology in science learning, such as blended learning and digital PBL. In 2024, there was a slight fluctuation, but it did not change the overall trend. The peak growth occurred in 2025, which saw the most significant surge in publications and indicated that this topic had entered a phase of rapid growth and become a major focus in science education research.

Meanwhile, in 2026, the recorded decrease in publications reflects the limited data available for the ongoing year rather than an actual decline in research interest. Overall, this numerical trend strictly indicates a significant expansion in publication frequency and a widening diversification of research topics. However, this surge in document volume does not automatically equate to theoretical stabilization; it remains to be critically evaluated whether this proliferation of literature translates into refined, high-impact pedagogical models suitable for specific programmatic adoption such as within natural science education programs or if it predominantly consists of repetitive, localized classroom implementations.

From a global perspective, this research growth tends to be dominated by countries with strong research capacity, while contributions from developing countries continue to grow. This opens up opportunities for further research to examine the application of PBL in diverse local contexts, particularly in science education in developing countries.

2. Productive Countries and Institution

The analysis revealed that publications on the topic of critical thinking and problem-based learning in science education are distributed globally, but are dominated by a few key countries. The United States tops the list as the most productive contributor, accounting for 24 articles (24.2% of the total dataset), reflecting its strong research ecosystem, funding support, and extensive international collaboration network. Indonesia follows in the second position with 18 published articles (18.1%), objectively establishing its standing as a primary contributor among developing nations. This quantitative output indicates that science education research in Indonesia, particularly that focused on learning innovations such as problem-based learning, is expanding rapidly. This contribution is supported by various universities, such as Jakarta State University, Yogyakarta State University, Sebelas Maret University, Malang State University, Ahmad Dahlan University, and Lampung University, which actively produce publications in this field.

Furthermore, several other countries, such as China, Malaysia, and India, have also demonstrated strong and consistent contributions in recent years. European countries like Spain, as well as others like Canada and Iran, have also contributed to enriching research in this field, albeit at more moderate levels. Meanwhile, contributions from countries like Turkey, Australia, South Africa, and Peru demonstrate the increasingly widespread distribution of research across regions. To fully contextualize how this global diversification impacts the theoretical trajectory of the field, it is necessary to contrast our structural findings with the existing literature. Table X provides a state-of-the-art comparison, mapping our thematic clusters against previous reviews to demonstrate the updated consensus regarding problem-based learning and critical thinking in science education.

Table 2. State-of-the-Art Comparison of Thematic Findings in PBL and Critical Thinking Research

Author(s) & Year	Research Focus	Methodological Approach	Key Limitations/Gaps Identified	Current Study's Updated Consensus & Cluster Mapping
Latif et al. (2018)	Critical thinking and communication in PBL.	Narrative Review	Heavily siloed in health education contexts; lacks generalizability to natural sciences.	Expands the scope beyond health domains. **Cluster 1 (Red)** demonstrates that pedagogical evaluation is now comprehensively applied across broader science curricula.
Matlala (2021)	PBL implementa	Qualitative Analysis	Focused predominantly on	Shifts focus from subjective perceptions

Author(s) & Year	Research Focus	Methodological Approach	Key Limitations/Gaps Identified	Current Study's Updated Consensus & Cluster Mapping
	tion and simulation.		subjective student learning perceptions rather than structural pedagogical mapping.	to mechanistic implementation. **Cluster 2 (Green)** maps how active learning structurally dictates problem-solving skill acquisition.
De Silva et al. (2023)	Global perceptions of PBL as a critical thinking tool.	Survey/Systematic Review	Contextually isolated; fails to capture the multidisciplinary evolution and global structural network.	**Cluster 3 (Blue)** establishes the macro-level conceptual nexus, proving the integration of PBL and CT has matured into multidisciplinary fields like ethnoscience and sustainability."

On the other hand, several countries such as Brazil, Norway, Nepal, Saudi Arabia, Taiwan, and Hungary contributed in more limited numbers, but still demonstrate that interest in this topic has reached a wide range of geographic contexts and educational systems. Overall, this distribution pattern indicates that while research remains dominated by countries with strong research capacity, the involvement of developing countries is increasing. This opens up opportunities for the development of more contextual and diverse research, particularly in examining the implementation of PBL and the development of CT in various educational settings.

3. Top Journals

Studies focusing on critical thinking within problem-based learning approaches in science education are spread across various international journals, but a few have emerged as primary hubs. Advances in Physiology Education and BMC Medical Education emerged as the most productive journals. The dominance of medical and physiology journals within a general "science education" query is not an artifact of the Boolean search string; rather, it reflects the historical origins and disproportionate application of PBL in medical diagnostics compared to the expected foundational STEM literature. This heavy skew raises valid questions regarding contextual drift—specifically, how clinical reasoning models translate to general science pedagogy. While medical PBL heavily emphasizes diagnostic triage, its core structural mechanisms—such as rigorous evidence evaluation, case-based investigation, and collaborative synthesis—are highly adaptable to pure science education contexts. For instance, these clinical reasoning structures can be directly translated into socioscientific reasoning models for undergraduate natural science education curricula, equipping pre-service teachers to systematically tackle

complex, multidisciplinary STEM issues. Furthermore, several journals, such as the Interdisciplinary Journal of Problem-Based Learning, Sustainability, Biochemistry and Molecular Biology Education, and PLoS ONE, show consistent contributions, reflecting that the study of critical thinking and PBL has expanded into interdisciplinary areas. Conversely, journals such as the Journal of Engineering Education Transformations, BMC Nursing, and Education Medica contribute at a more moderate level, indicating that despite the broad scope, high-impact pedagogical mapping remains concentrated in a few key clinical and interdisciplinary hubs.

Overall, this pattern suggests that research in this field tends to be concentrated in specific journals that focus on practice-based education, particularly in the areas of health and problem-based learning. However, the wide distribution of publications also indicates that this topic is interdisciplinary and continues to expand across various disciplines.

B. Science Mapping Visualization

1. Network Visualization

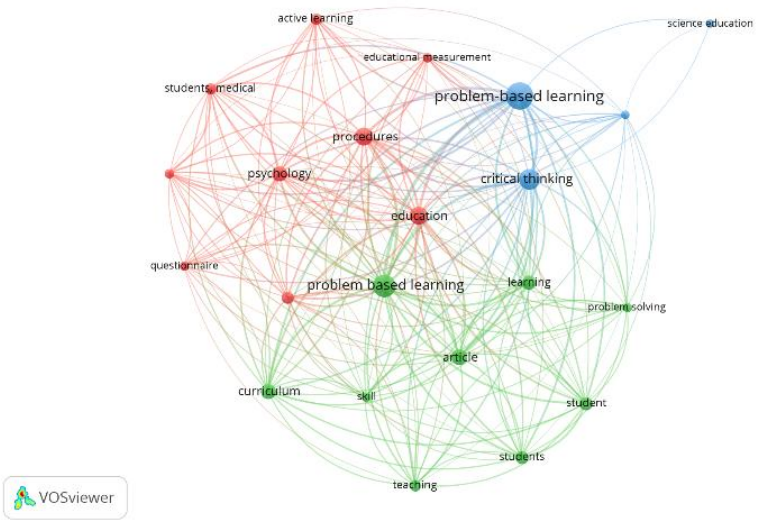


Figure 3. Network Visualization

Network visualization shows that critical thinking and problem-based learning (PBL) act as key nodes connecting various concepts in science education. The resulting network structure demonstrates an integrated research field, where the interrelationships between keywords reflect multidisciplinary developments. This demonstrates that research does not focus solely on one aspect, but encompasses the conceptual, implementation, and evaluation dimensions of learning simultaneously. The mapping results indicate the organic formation of three main clusters representing major themes in this field. To clarify the computational mechanics, these three clusters were generated as the default output of VOSviewer's modularity-based clustering algorithm; the software grouped these specific nodes together based strictly on

their high co-occurrence frequencies and strong total link strengths, without any manual manipulation of the cluster resolution parameters to force a specific structural outcome.

The first cluster (red) represents pedagogical approaches and learning evaluation. Dominant keywords in this cluster include education, active learning, educational measurement, procedures, psychology, and questionnaires, alongside nodes highlighting the target demographic through variants like medical students. This demonstrates that research focuses not only on the implementation of PBL but also on how its effectiveness is measured through various evaluation instruments. The presence of terms such as psychology indicates that cognitive and behavioral aspects are important considerations, particularly in understanding how critical thinking processes develop in problem-based learning. Thus, this cluster plays a role in ensuring that PBL implementation can be evaluated systematically and evidence-based.

The second cluster (green) focuses on learning implementation and its impact on learning outcomes. Keywords such as problem-based learning, learning, teaching, curriculum, skills, and problem-solving (along with various morphological nodes representing the student body) indicate that research in this cluster comprehensively focuses on the practical classroom implementation of PBL. The strong linkages (high total link strength) between these keywords indicate that PBL is consistently studied as a primary strategy for improving higher-order thinking skills. Furthermore, the close relationship between these pedagogical variables and problem-solving indicates that successful PBL implementation depends heavily on active engagement in the learning process.

Meanwhile, the third cluster (blue) represents the conceptual core of the research field, with key keywords such as critical thinking, problem-based learning, and science education. This cluster demonstrates a very strong connection between the core concepts, which serve as the primary foundation of the research. This indicates that most studies position critical thinking as the primary objective, PBL as the approach used, and science education as the context of its application. The high level of interconnectedness within this cluster demonstrates the consistency of research direction and the central role of these three concepts in building the theoretical framework of this field. The implication is that future research should focus not only on developing learning models but also on strengthening valid evaluations and integrating theory and practice. Furthermore, the strong correlation between keywords suggests that critical thinking and PBL will remain a primary focus in science learning development, particularly in addressing the demands of 21st-century skills that emphasize critical thinking, problem-solving, and active learning.

2. Overlay Visualization

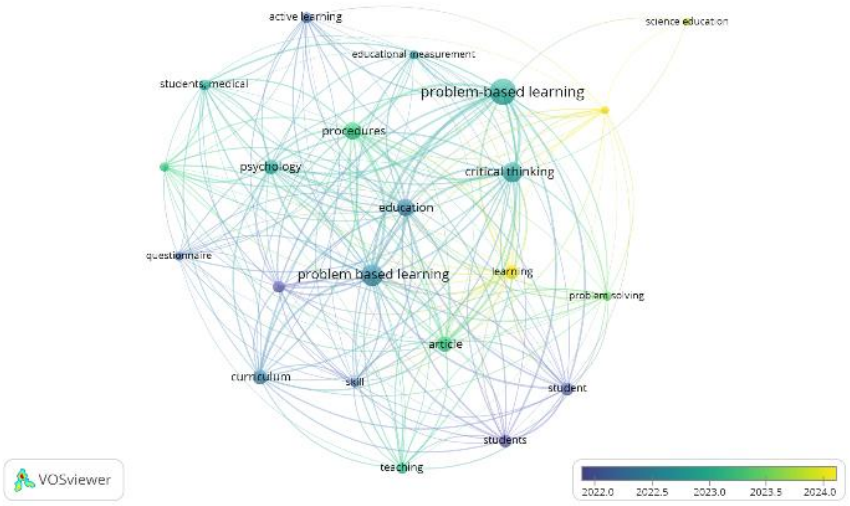


Figure 4. Overlay Visualization

The analysis shows that research topics in the initial phase focused more on basic aspects of learning and evaluation. This is evident from the emergence of keywords such as "students," "student," "questionnaire," "curriculum," "skills," and "active learning," which were among the topics that developed earlier. The focus of research at this stage tended to discuss student characteristics, curriculum development, learning activities, and the use of assessment instruments to measure the effectiveness of PBL implementation.

Subsequently, research began to shift to a more in-depth discussion of the learning process and student psychology. Keywords such as "psychology," "procedures," "teaching," and "article" indicate that researchers' attention was not solely focused on the implementation of PBL, but also on how learning strategies and students' psychological state influence the development of critical thinking skills. Furthermore, the most recent and emerging topics were "learning," "problem-solving," and "science education." The emergence of these topics indicates that current research directions increasingly highlight the cultivation of higher-order thinking skills, especially problem-solving abilities in the context of science education. This indicates that research is no longer solely focused on the effectiveness of learning methods, but also on how learning can shape competencies relevant to 21st-century needs.

Furthermore, key keywords such as critical thinking and problem-based learning remain central and consistently appear across research periods. This demonstrates that these two concepts serve as the primary foundation for developing science education research and are strongly linked to various other topics. Overall, the analysis reveals a shift in research direction from an initial focus on learning implementation and evaluation to strengthening critical thinking abilities, problem-solving skills, and developing more innovative

science learning. This demonstrates that research on critical thinking and problem-based learning (PBL) continues to evolve and is increasingly relevant in supporting learning oriented toward 21st-century skills.

3. Denisty Visualization

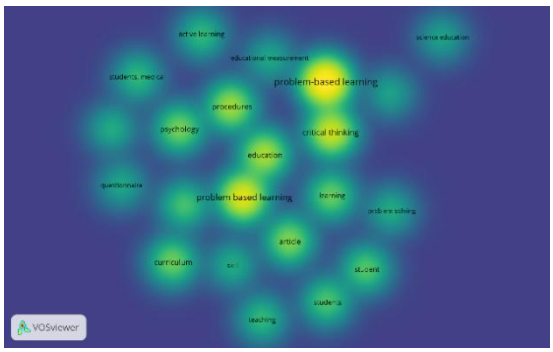


Figure 5. Denisty Visualization

Based on the visualization, the densest areas are identified by the keywords PBL and CT . The high density in these areas indicates that these three topics are the main focus of research and the most widely studied in science education. The dominance of these keywords indicates that most research focuses on the application of PBL as a learning approach to develop students' critical thinking skills.

High density is also seen in the keywords education, learning, and procedures. This indicates that research in this field discusses the learning process, implementation strategies, and procedures for implementing problem-based learning models. Furthermore, the emergence of keywords such as psychology and educational measurement indicates that psychological aspects and learning evaluation are also important concerns in research related to critical thinking and PBL.

Meanwhile, several areas with lower density are seen in the keywords science education, problem solving, students, student, teaching, skill, curriculum, and questionnaire. The low density of these topics indicates that research has not yet explored the relationship between PBL and the development of specific skills in the context of science education in greater depth. The keyword science education, which is in a relatively sparse area, indicates that there is still significant research opportunity related to the application of critical thinking and PBL, more specifically in science learning. In addition, topics such as problem solving, teaching, and curriculum also show potential for development, especially in examining learning design, developing 21st-century skills-based curriculum, and more innovative teaching strategies.

C. Critical Thinking in Science Education

The synthesis of articles shows that research on critical thinking in science education has experienced rapid development in recent years. Critical thinking skills

are viewed as one of the core competencies of the 21st century, crucial for science learning because they help students understand scientific phenomena logically, analytically, and evidence-based. Within the context of science education, critical thinking relates not only to the ability to memorize concepts but also to the ability to evaluate information, connect various scientific concepts, and solve problems systematically.

Most research indicates that the development of critical thinking is achieved through active learning, scientific inquiry, collaborative learning, and problem-solving. These approaches provide opportunities for students to be more active in constructing knowledge rather than simply passively receiving information from teachers. Therefore, research in science education has begun to integrate investigative activities, scientific argumentation, and problem-based discussions to improve students' higher-order thinking skills. According to Table 3, research on critical thinking in science education is dominated by the development of analytical thinking, reasoning, HOTS, and scientific inquiry. Active learning approaches are the primary strategy for improving students HOTS

Table 3. Synthesis of Research on Critical Thinking in Science Education

No	Citation	Research	Focus Findings
1	(Ge et al., 2025)	Critical thinking and clinical reasoning	PBL improves students' critical thinking skills
2	(Purkat et al., 2026)	Scientific inquiry and reasoning	Inquiry learning improves students' scientific reasoning
3	(Mohebbi et al., 2022)	Analytical thinking in blended learning	Blended learning supports analytical thinking skills
4	(Victor Quiñones Borda, 2024)	Mathematical modeling and problem solving	Contextual modeling improves students' analytical skills
5	(Ruan et al., 2025)	Competition-based learning	Competitive activities improve students' critical thinking

Research by Ge *et al.*, (2025) shows that implementing PBL can improve students' CT skill through problem investigation activities and collaborative discussions. In this study, students were encouraged to analyze cases in depth, identify solutions, and develop arguments based on scientific data.

Research by Mohebbi *et al.*, (2022) also found that implementing a blended flipped classroom had a positive impact on students' analytical thinking skills. This learning model allows students to study the material independently through digital media before engaging in discussion and problem-solving activities in class. This allows classroom learning time to be more focused on HOTS activities such as analysis, evaluation, and scientific argumentation.

On the other hand, research by Victor Quiñones Borda, (2024) shows that the use of mathematical modeling based on contextual problems can improve students' analytical and decision-making skills. Model-based learning helps students connect scientific concepts to real-life situations, thereby significantly developing critical thinking skills. This demonstrates that modern science education emphasizes not only conceptual understanding but also the ability to apply those concepts to solve real-life problems.

Technological developments are also beginning to influence the direction of critical thinking research in science education. Several recent studies have begun to integrate digital learning, blended learning, artificial intelligence, and gamification in developing students' critical thinking skills. The use of digital technology is considered capable of creating a more flexible, interactive learning environment and supporting both independent and collaborative problem-solving activities.

However, the synthesis of results shows that most research remains narrowly focused on generic evaluations of higher-order thinking skills (HOTS) and standard student learning outcomes. The integration of adaptive learning, AI-assisted learning, sustainability issues, and socio-scientific issues in developing critical thinking is not merely limited; its absence represents a critical pedagogical bottleneck. This systemic gap highlights a failure to integrate localized, complex contexts into mainstream PBL models, leaving science curricula ill-equipped to prepare students for real-world socio-environmental crises. To address this, future instructional roadmaps must transition toward an Ethno-AI framework, seamlessly embedding artificial intelligence into local ethnoscience contexts. By grounding PBL in advanced socioscientific reasoning (SSR) and 'Futures Thinking'—such as utilizing STEM-driven disaster mitigation models for earthquake and tsunami literacy—educators can dynamically operationalize critical thinking for global resilience. Furthermore, because most current research is isolated within higher education, deploying this Ethno-AI and SSR-based instructional roadmap at the elementary and secondary levels is urgently required to build foundational scientific literacy.

D. Problem-Based Learning in Science Education

Synthesis results indicate that problem-based learning (PBL) is one of the most dominant learning approaches in science education research. This learning model is used because it is considered capable of creating active, contextual, and student-centered learning. In its implementation, PBL places real-world problems as the primary trigger for learning activities, so that students not only learn concepts but also learn how to use those concepts to solve problems.

Most research indicates that PBL is implemented through group discussions, collaborative learning, scientific inquiry, and problem investigation. This approach assists students in developing communication, cooperation, and the enhancement of problem-solving skills throughout the learning process. However, its distinct appropriateness for contemporary science education relies on its unique structural advantages when compared to other dominant active learning models present in the literature, such as Case-Based Learning (CBL). While CBL is highly effective for guiding students through structured, predefined diagnostic exercises, the synthesized literature demonstrates that PBL demands a significantly higher degree of investigative autonomy. Because PBL utilizes ill-structured, open-ended problems rather than closed cases, it uniquely forces students to independently navigate the actual friction of scientific inquiry, formulate hypotheses from unstructured data, and synthesize evidence-based solutions—competencies that are critical for addressing unpredictable, real-world socioscientific challenges.

Research by Susanto et al. (2022) shows that the use of PBL-based e-books in science learning can create more interactive and contextual learning. The use of digital

media helps students understand science concepts through problem exploration and independent investigation activities. Furthermore, the integration of technology in PBL also helps increase student motivation and engagement during the learning process.

Table 4. Research Synthesis on Problem-Based Learning in Science Education

No	Citation	Research	Focus Findings
1	(Susanto et al., 2022)	E-book based on Problem-Based Learning	PBL creates more interactive learning
2	(Ordóñez Fernández et al., 2026)	Collaborative learning in PBL	PBL increases student learning engagement
3	(Ruan et al., 2025)	Competition-based problem learning	PBL increases student motivation and participation
4	(Ge et al., 2025)	Implementation of PBL in learning	PBL supports investigation and problem solving
5	(Purkat et al., 2026)	Inquiry-based problem learning	PBL helps students' scientific investigation

Based on the data extracted in Table 4, the dominance of collaborative learning, inquiry, and problem-solving metrics signifies a major pedagogical shift in science education: instruction is fundamentally transitioning from teacher-directed knowledge transmission to socially constructed, autonomous scientific investigation. This structural shift means that PBL is no longer treated merely as an isolated classroom activity, but as a comprehensive pedagogical framework that mirrors the actual epistemic practices of scientific communities. For instance, integrating collaborative frameworks (Ordóñez Fernández et al., 2026) and inquiry-based problem solving (Purkat et al., 2026) directly translates to heightened student engagement, as learners are forced to actively negotiate hypotheses, exchange ideas, and defend evidence-based solutions. Consequently, PBL functions as a critical mechanism for developing both rigorous analytical reasoning and the essential social competencies required for scientific communication. Furthermore, the introduction of competition-based learning (Ruan et al., 2025) and interactive digital scaffolds (Susanto et al., 2022) indicates that this pedagogical shift is evolving to leverage both intrinsic motivation and technological integration. Therefore, the convergence of these themes within the VOSviewer network confirms that modern PBL models are successfully reshaping science curricula to prioritize dynamic, investigative competencies over rote memorization, necessitating future research into highly adaptive, technology-driven PBL models.

CONCLUSION

This study concludes that the intersection of critical thinking and problem-based learning (PBL) in science education represents a fundamental structural paradigm shift rather than a mere increase in publication volume. The bibliometric mapping reveals strong conceptual linkages confirming that PBL is rapidly evolving from a localized instructional method into a comprehensive, multidisciplinary theoretical framework. For program-level curriculum design, particularly within Natural Science Education Programs (Prodi Pendidikan IPA), this shift dictates an urgent transition toward integrating advanced socioscientific reasoning and

technology-enabled frameworks to systematically address complex modern challenges.

While the bibliometric co-occurrence networks strictly prove that global researchers are concurrently prioritizing these theoretical variables, the qualitative synthesis of the systematic literature review validates the actual pedagogical implications of these linkages. The SLR findings indicate that when PBL is systematically implemented through collaborative inquiry and ill-structured problem investigation, it successfully functions as a structural scaffold for developing critical thinking, analytical reasoning, and scientific communication. Practically, these combined insights provide science educators with a validated, data-driven blueprint to design active learning environments that prioritize autonomous investigation over traditional knowledge transmission.

A distinct practical advantage of this structural evolution is the emerging capacity to integrate blended learning, digital simulations, and AI-assisted scaffolds directly within the PBL framework. By adopting these technology-driven models, science educators can dynamically simulate real-world crises—such as local disaster mitigation scenarios for earthquake and tsunami literacy—offering students highly contextualized environments that safely bridge the gap between theoretical science and practical environmental resilience.

Despite these insights, several methodological limitations must be acknowledged. First, data extraction was exclusively confined to the Scopus database, which, while robust, may exclude relevant pedagogical studies indexed in regional or specialized databases. Second, the bibliometric mapping inherently focuses on metadata and keyword co-occurrences, meaning it visualizes theoretical trajectories but cannot independently measure the qualitative efficacy of the interventions. Finally, restricting the dataset to English-language publications may introduce geographical bias, potentially obscuring localized science education innovations implemented in non-English contexts.

Ultimately, this integrated review comprehensively maps the trajectory of PBL and critical thinking, offering a strategic foundation for modernizing science education. To advance this field, future research should prioritize: (1) investigating the integration of artificial intelligence and ethnoscience within PBL frameworks to directly address localized socio-environmental challenges; (2) conducting longitudinal, quasi-experimental studies to measure the long-term retention of critical thinking skills cultivated through these specific methods; and (3) expanding empirical evaluations beyond higher education to establish adaptive PBL frameworks specifically tailored for primary and secondary natural science curricula.

RECOMMENDATION

Despite these insights, several methodological limitations must be acknowledged before outlining future directions. First, data extraction was exclusively confined to the Scopus database. While ensuring international rigor, this

reliance inherently excludes highly relevant regional pedagogical implementations—particularly those documented in national Sinta-accredited journals that focus on applied science education in developing contexts. Second, the restriction to English-language articles introduces geographical bias. Finally, while the SLR robustly synthesized the empirical findings of the 99 included full texts, the preceding bibliometric mapping inherently visualized only metadata and keyword relationships; thus, the network graphs alone cannot independently measure pedagogical efficacy without the accompanying qualitative synthesis.

To address the structural gaps identified in the VOSviewer density analysis—where specific skills like problem-solving and primary-level curriculum implementation appeared in sparse, low-density zones—future research must transition from generic observations to a focused instructional roadmap. The sparsity of the current literature graph dictates an urgent need for targeted empirical designs, specifically longitudinal and quasi-experimental studies, to test the integration of advanced frameworks. Researchers must theoretically justify and explore interdisciplinary themes that operationalize these gaps; for example, merging advanced socioscientific reasoning (SSR) and 'Futures Thinking' to develop robust disaster mitigation modules. Furthermore, the integration of Ethno-AI frameworks, combining artificial intelligence with local ethnoscience, is structurally necessary to localize science education curricula. Finally, to ensure these pedagogical innovations are not isolated, empirical evaluations must expand beyond higher education to establish adaptive PBL frameworks specifically tailored for primary and secondary natural science programs

Author Contributions

Santi Rahmawati: conceptualization, methodology, formal analysis, investigation, data curation, and writing, original draft preparation; Livia Diyah Yusnita: literature review, data curation, investigation, and writing, review and editing; Findi Rahma Saputri: literature review, data curation, investigation, and writing, review and editing; Kiki Septaria: supervision, validation, and writing, review and editing; Namira Putri Jawawi: literature review, data curation, and writing, review and editing; Nihla Tasfirul Kholisho: literature review, data curation, and writing, review and editing. All authors have read and agreed to the published version of the manuscript.

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Conflict of interests

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