Jurnal Penelitian Pembelajaran Fisika
Vol. 17 Issue 2 – April 2026, p108-122
p-ISSN 2086-2407, e-ISSN 2549-886X
Available Online at http://journal2.upgris.ac.id/index.php/JP2F
DOI: 10.26877/jp2f.v17i2.3443

Integrating Problem-Based Learning into Science Education at the Secondary Level: Bibliometric Insights into Development and Future Research

Lintang Auliya Kurdiati[1,2] **and Sabar Nurohman**[1]
[1]Master of Natural Science Education Study Program, Universitas Negeri Yogyakarta, Indonesia

[2]E-mail: lintangauliya03@gmail.com

Received: 2 February 2026. Accepted: 29 April 2026. Published:30 April 2026.

Abstract. Problem-Based Learning (PBL) is increasingly recognized as an instructional approach that supports higher-order thinking, conceptual understanding, and authentic problem solving in secondary science education. Although numerous empirical studies have examined the effectiveness of PBL, a comprehensive understanding of how this research field has developed, structured its themes, and evolved over time remains limited. This study aims to map the development and intellectual landscape of research on the integration of PBL in secondary science education. A bibliometric and network analysis was conducted on 173 peer-reviewed journal articles published between 2015 and 2025 and indexed in the Scopus database. Publication trends, authorship patterns, keyword co-occurrence, and thematic structures were analyzed using bibliometric indicators and visualization techniques. The results show a steady growth in publications, with research strongly centered on pedagogical and curricular issues, positioning PBL as the main conceptual hub. At the same time, emerging themes related to STEM education, digital learning, artificial intelligence, and competency development indicate a broadening research focus. Overall, the findings demonstrate both consolidation and diversification within the field. These insights offer a systematic foundation for guiding future research agendas and supporting evidence-based implementation of PBL in secondary science education.

Keywords: bibliometric, problem-based learning, science education, secondary education

1. Introduction

Secondary science education is often characterized by instructional practices that prioritize content coverage and procedural problem-solving over higher-order thinking and meaningful application [1–4]. Such approaches have been widely associated with fragmented conceptual understanding and limited transfer of scientific knowledge to unfamiliar contexts [5–7]. As scientific challenges increasingly demand integrative reasoning and adaptive problem-solving, concerns have grown regarding the adequacy of traditional pedagogical models in preparing secondary students for complex scientific thinking [8–10]. In response to these limitations, Problem-Based Learning (PBL) has gained recognition as a pedagogical approach that emphasizes student agency, inquiry, and authentic problem contexts [11–13]. Empirical research has repeatedly demonstrated the educational value of PBL in science learning. Foundational studies by [14] show that students in PBL environments develop deeper and more coherent conceptual understanding compared to those in teacher-centered classrooms. Similarly, quasi-experimental research by [15] indicates that secondary students exposed to PBL exhibit higher levels of problem-solving performance and self-directed learning. These findings are further corroborated by meta-analytical evidence reporting consistent positive effects of PBL across science disciplines.

The pedagogical relevance of PBL becomes particularly salient at the secondary level, where learners are expected to move beyond rote learning toward abstract reasoning and conceptual integration [16–18]. However, secondary science students continue to experience persistent difficulties in applying

scientific concepts across contexts and in coordinating multiple ideas when addressing complex problems [19–21]. Studies by [22] demonstrate that PBL environments support the development of epistemic agency by engaging students in hypothesis generation, evidence evaluation, and justification of conclusions. These competencies are widely recognized as central to scientific literacy and disciplinary thinking in secondary science education. Despite strong empirical support, the research landscape on PBL in secondary science education remains uneven and fragmented. Bibliometric studies by [23] reveal that a substantial proportion of PBL research has been conducted in higher education contexts, particularly in medical and engineering education, with comparatively fewer studies focusing on secondary science classrooms. Moreover, reviews by [24] suggest that existing research often prioritizes learning outcomes while offering limited analysis of instructional design features, disciplinary variations, or longitudinal impacts. This pattern indicates a lack of comprehensive understanding of how PBL research in secondary science education has evolved and diversified over time.

Most existing syntheses of PBL research rely on narrative or systematic review methodologies. While these approaches provide valuable thematic insights, they are inherently limited in capturing large-scale publication trends, intellectual structures, and patterns of scholarly collaboration. Methodological analyses show that bibliometric and network-based approaches are particularly effective for revealing thematic clusters, influential contributors, and emerging research directions within complex research fields [25–28]. However, such approaches have rarely been applied to map PBL research specifically within the domain of secondary science education. To address this gap, the present study employs a bibliometric and network analysis to examine the integration of PBL into secondary science education. By analyzing publication trends, authorship patterns, keyword co-occurrence, and thematic evolution, this study provides a systematic and data-driven overview of the field's development. The findings are intended to inform future research agendas and support evidence-based pedagogical innovation aimed at strengthening the role of PBL in secondary science education.

1.1. *Research Aim and Research Questions*

The aim of this study is to systematically map and analyze the development, structure, and intellectual landscape of research on the integration of Problem-Based Learning (PBL) into secondary science education using bibliometric and network analysis techniques. Specifically, this study seeks to identify publication trends, influential contributors, thematic clusters, and emerging research directions that shape the evolution of PBL in secondary-level science learning.

To achieve this aim, the study examines (1) how research on PBL in secondary science education has evolved over time in terms of publication output, thereby revealing growth patterns and the trajectory of scholarly interest in the field. It also identifies (2) the authors, institutions, and journals that have played central roles in advancing PBL research, highlighting the key contributors and sources that shape the academic discourse. Furthermore, the study explores (3) the major research themes and thematic clusters that characterize the literature, providing insight into dominant and developing areas of inquiry. In addition, it analyzes (4) how key concepts and keywords are interconnected within the PBL literature through co-occurrence networks, in order to uncover the underlying conceptual structure of the field. Finally, the study investigates (5) emerging themes and underexplored areas that indicate potential directions for future research in PBL within secondary science education.

2. Method

2.1. *Research Design*

This study employed the Systematic Literature Network Analysis (SLNA) approach, which integrates a Systematic Literature Review (SLR) guided by the PRISMA framework with bibliometric network analysis. This approach enables a systematic and transparent synthesis of the literature by combining rigorous screening procedures with quantitative mapping of scholarly relationships. The SLR component ensured methodological transparency and reproducibility, while bibliometric analysis supported the exploration of publication structures, research patterns, and thematic developments within the field. The bibliometric analysis was conducted using Biblioshiny and VOSviewer, allowing both qualitative and quantitative examination of the literature. These tools were used to identify co-authorship

networks, keyword co-occurrence patterns, citation relationships, and evolving thematic clusters related to PBL in secondary science education.

2.2. *Data Sources and Search Strategy*

Data were retrieved exclusively from the Scopus database, covering publications from 2015 to 2025. Scopus was selected because it provides an integrated search and filtering system that supports systematic literature reviews and bibliometric analyses through standardized indexing, advanced query functions, and subject classification. The search strategy followed the search and filter mechanisms embedded within the Scopus system to ensure consistency, transparency, and reproducibility of the retrieval process.

The search was conducted using Boolean operators and field-specific querying available in Scopus. Boolean logic was applied to combine core conceptual terms related to PBL, science, secondary education, and educational contexts, ensuring that only publications in which these concepts appeared jointly were retrieved. The use of the TITLE-ABS-KEY field limited the search to articles in which the keywords were explicitly present in the title, abstract, or author keywords, thereby increasing the relevance of the dataset and reducing the inclusion of marginally related studies.Accordingly, the following search query was applied through the Scopus search interface: *TITLE-ABS-KEY (problem AND based AND learning AND science AND secondary AND education) AND PUBYEAR > 2014 AND PUBYEAR < 2027 AND (LIMIT-TO (SUBJAREA, "SOCI")) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (LANGUAGE, "English"))*. Additional filtering options provided by the Scopus system were used to restrict the results to peer reviewed journal articles written in English and indexed within the social sciences subject area. To maintain relevance and consistency, conference papers, book chapters, review articles, and non-research documents were excluded from the dataset.

2.3. *Study Selection Process and Data Analysis*

To provide a transparent overview of the article selection procedure, the screening and inclusion process was conducted in accordance with the PRISMA stages, encompassing identification, screening, eligibility, and inclusion. The initial search yielded 695 publications, which were subsequently screened based on predefined inclusion and exclusion criteria. Figure 1 presents the PRISMA flow diagram illustrating the step-by-step selection process applied in this study.

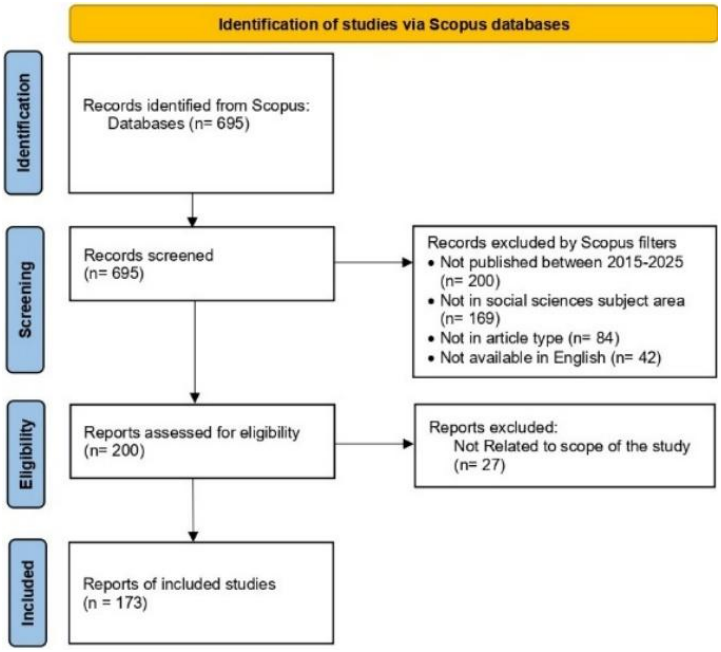

Figure 1. Prisma flow diagram.

Following the screening and eligibility assessment illustrated in Figure 1, irrelevant records and duplicate entries were removed. As a result of this multi-stage filtering process, 173 articles were retained for the final bibliometric analysis. This systematic selection procedure ensured that the final dataset accurately represented research trends and developments in PBL within secondary science education over the selected time period. Metadata from the selected articles were exported in RIS and BibTeX formats and analyzed using VOSviewer and Biblioshiny, respectively. VOSviewer was employed to visualize bibliometric networks and structural relationships among publications, including co-authorship and citation linkages. Biblioshiny supported statistical analyses of publication trends, keyword frequencies, collaboration patterns, and thematic evolution over time. Together, these analytical procedures enabled a comprehensive examination of research development and the identification of future research directions in the field of secondary science education through PBL

3. Results and Discussion

3.1. *Overview of the Included Studies (2015–2025)*

An initial overview of the included studies provides a descriptive foundation for understanding the scope, scale, and temporal development of research on PBL in secondary science education. By examining publication trends and core bibliometric characteristics, this overview highlights how scholarly attention to this topic has evolved over the selected time span. To illustrate the temporal distribution of publications, the annual number of relevant articles published between 2015 and 2025 is presented in Figure 2.

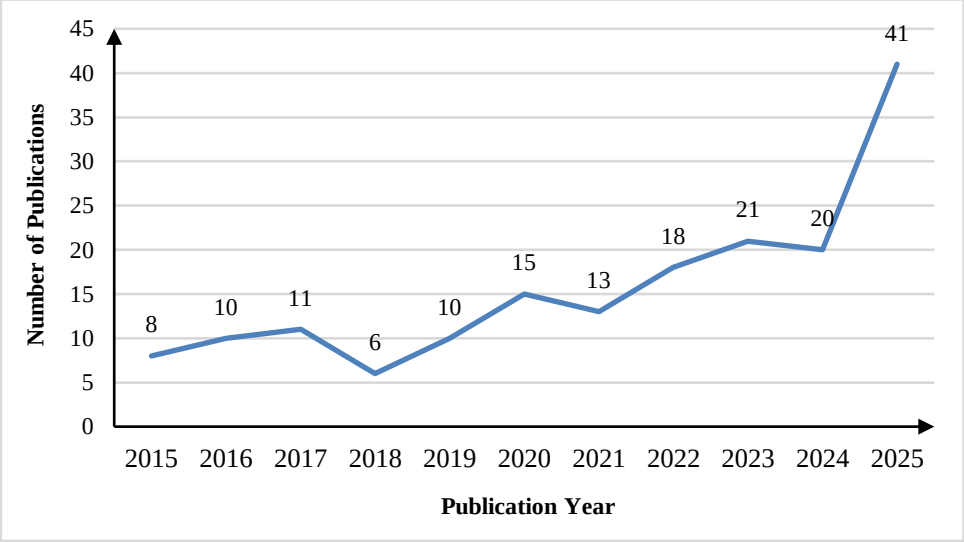

Figure 2. Number of relevant publications per year.

As shown in Figure 2, research output on PBL in secondary science education demonstrates a generally upward trajectory over the examined period. Early publication activity between 2015 and 2017 remained modest, followed by a noticeable dip in 2018. From 2019 onward, the number of publications increased steadily, with a marked acceleration after 2020. The most substantial growth occurred in the later years, culminating in a sharp rise in 2025. This pattern suggests a growing and sustained scholarly interest in the application and investigation of PBL within secondary science contexts, potentially influenced by broader educational reforms, curriculum innovation, and increased attention to active learning pedagogies. Beyond temporal trends, a broader bibliometric profile of the dataset is necessary to contextualize the structural characteristics of the included publications. Table 1 summarizes the main information of the analyzed documents, including publication output, authorship patterns, and collaboration indicators.

The information presented in Table 1 reflects a diverse and expanding body of literature. The dataset spans a ten-year period and comprises 173 peer-reviewed articles published across 109 sources,

indicating a wide dispersion of research outlets rather than concentration within a small number of journals. The annual growth rate of 17.75 percent further confirms the increasing momentum of research in this area. With an average document age of 4.49 years and an average of 11.12 citations per article, the literature demonstrates both recency and moderate scholarly impact. A total of 515 authors contributed to the included studies, with relatively few single-authored publications. The average of 3.08 co-authors per document and an international co-authorship rate exceeding 16 percent indicate a collaborative research culture, albeit with room for broader cross-national engagement. Collectively, these characteristics suggest that research on PBL in secondary science education has developed into a dynamic and collaborative field, providing a solid empirical base for further thematic and network-based analyses in subsequent sections.

Table 1. Main information of publications.

Description	Results
Main Information about Data	
Timespan	2015:2025
Sources (Journals, Books, etc)	109
Documents	173
Annual Growth Rate %	17.75
Document Average Age	4.49
Average citations per doc	11.12
References	1594
Authors	
Authors	515
Authors of single-authored docs	19
Authors Collaboration	
Single-authored docs	19
Co-Authors per Doc	3.08
International co-authorships %	16.18

3.2. *Most Prolific Contributors*

An examination of the most prolific contributors provides insight into the geographical distribution, institutional concentration, and influential works shaping research on PBL in secondary science education. By analyzing contributions at the country, institutional, and article levels, this subsection highlights where scholarly activity is most concentrated and how collaborative patterns and citation impact differ across contexts. To identify the countries that contribute most actively to the field, Table 2 presents the distribution of publications by country, along with indicators of Single Country Publications (SCP) and Multiple Country Publications (MCP).

Table 2. Most prolific countries

Country	Articles		SCP		MCP	
	N	%	N	%	N	%
United States	21	12.1	18	85.7	3	14.3
Spain	13	7.5	11	84.6	2	15.4
China	9	5.2	4	44.4	5	55.6
Malaysia	6	3.5	5	83.3	1	16.7
Germany	5	2.9	4	80.0	1	20.0
Indonesia	5	2.9	4	80.0	1	20.0
Netherlands	5	2.9	5	100.0	0	0.0
Turkey	5	2.9	4	80.0	1	20.0
Hong Kong	4	2.3	3	75.0	1	25.0
Sweden	4	2.3	2	50.0	2	50.0

The data in Table 2 indicate that the United States leads in research output, accounting for the highest number of publications, the majority of which are produced through single-country collaborations. Spain

and China follow as prominent contributors, although their collaboration patterns differ substantially. While Spain shows a strong dominance of single-country publications, China demonstrates a higher proportion of multi-country collaborations, suggesting a more internationally connected research profile. Contributions from Malaysia, Germany, Indonesia, the Netherlands, and Turkey reflect a geographically diverse research landscape, with varying balances between domestic and international collaboration. Overall, these patterns indicate that although research productivity remains concentrated in a limited number of countries, international collaboration plays an increasingly visible role in shaping knowledge production in this field. Beyond overall publication counts, it is important to consider how research productivity has evolved over time across leading countries. Figure 3 illustrates the production growth of the top contributing countries throughout the study period.

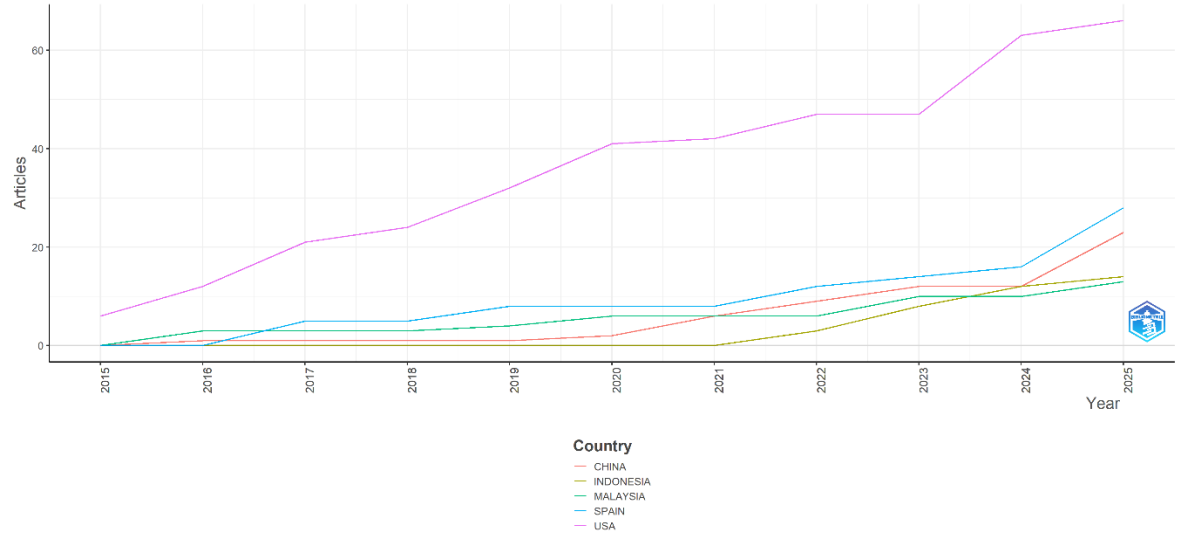

Figure 3. Production growth of the top 10 countries

As shown in Figure 3, the United States exhibits a consistently strong and accelerating growth trend across the entire period, reinforcing its central role in advancing research on PBL in secondary science education. Spain and China display pronounced growth trajectories in the later years, indicating a rapid expansion of research activity after an initial period of limited output. Malaysia shows steady and incremental growth, while Indonesia emerges more recently with a notable increase in publications after 2022. These longitudinal patterns highlight a gradual shift from early dominance by a few countries toward broader global participation, particularly from emerging research contexts in Asia. In addition to national contributions, institutional productivity offers further insight into the centers of research activity within the field. Table 3 summarizes the most prolific affiliations based on publication output.

Table 3. Most prolific affiliation

Affiliation	Articles
University of Aveiro	5
LSU Health New Orleans School of Medicine	4
Universitat Rovira i Virgili	4
Universiti Kebangsaan Malaysia	4
Charles University	3
East China Normal University	3
Hassan II University of Casablanca	3
Louisiana State University Health Sciences Center	3
Penn State College of Medicine	3
Eindhoven University of Technology	3

Table 3 reveals that research output is distributed across a range of institutions rather than being dominated by a single organization. Universities such as the University of Aveiro, LSU Health New Orleans School of Medicine and *Universitat Rovira i Virgili* emerge as key institutional contributors, alongside several universities from Europe, Asia, Africa, and North America. This distribution suggests that research on PBL in secondary science education is supported by a diverse institutional base, reflecting cross-regional engagement and the absence of a narrowly centralized research hub. While productivity reflects research activity, citation impact provides an indication of scholarly influence. To capture this dimension, Table 4 presents the most cited articles within the dataset.

Table 4. Most cited articles

Rank	Article	Authors	Journal	TC	C/Y
1	How do students generate ideas together in scientific creativity tasks through computer-based mind mapping?	[29]	Computers & Education	88	17.60
2	Fostering students' 21st century skills through Project Oriented Problem Based Learning (POPBL) in integrated STEM education program	[30]	Asia-Pacific Forum on Science Learning and Teaching	69	6.27
3	Characterizing Students' 4C Skills Development During Problem-based Digital Making	[31]	Journal of Science Education and Technology	56	11.20
4	Effectiveness of Problem-Based Learning on Secondary Students' Achievement in Science: A Meta-Analysis	[32]	International Journal of Interaction	22	3.67
5	Problem-based learning with metacognitive prompts for enhancing argumentation and critical thinking of secondary school students	[33]	EURASIA Journal of Mathematics, Science and Technology Education	18	3.60

The most cited articles listed in Table 4 predominantly focus on skill development, creativity, digital learning environments, and meta-analytic evaluations of PBL. The prominence of articles published in high-impact journals such as Computers & Education and the Journal of Science Education and Technology underscores the interdisciplinary and pedagogical relevance of the field. The relatively high citation rates per year for several recent publications indicate sustained scholarly attention and suggest that research on PBL in secondary science education continues to resonate with contemporary educational priorities.

3.3. *Thematic Map*

To further explore the intellectual structure of research on PBL in secondary science education, a thematic map was generated to examine the distribution and developmental status of key research themes. This analysis position's themes based on their centrality and density, allowing an assessment of their relevance within the field as well as their internal conceptual development. The resulting thematic configuration is presented in Figure 4.

As illustrated in Figure 4, several themes are positioned within the motor themes quadrant, indicating high relevance and strong internal development. PBL, education, and academic achievement emerge as central drivers of the field, reflecting a sustained focus on instructional effectiveness and learning outcomes. Closely associated themes such as secondary education, e-learning, and motivation further reinforce the pedagogical orientation of the literature, suggesting that research increasingly integrates PBL with digital learning environments and affective dimensions of student engagement.

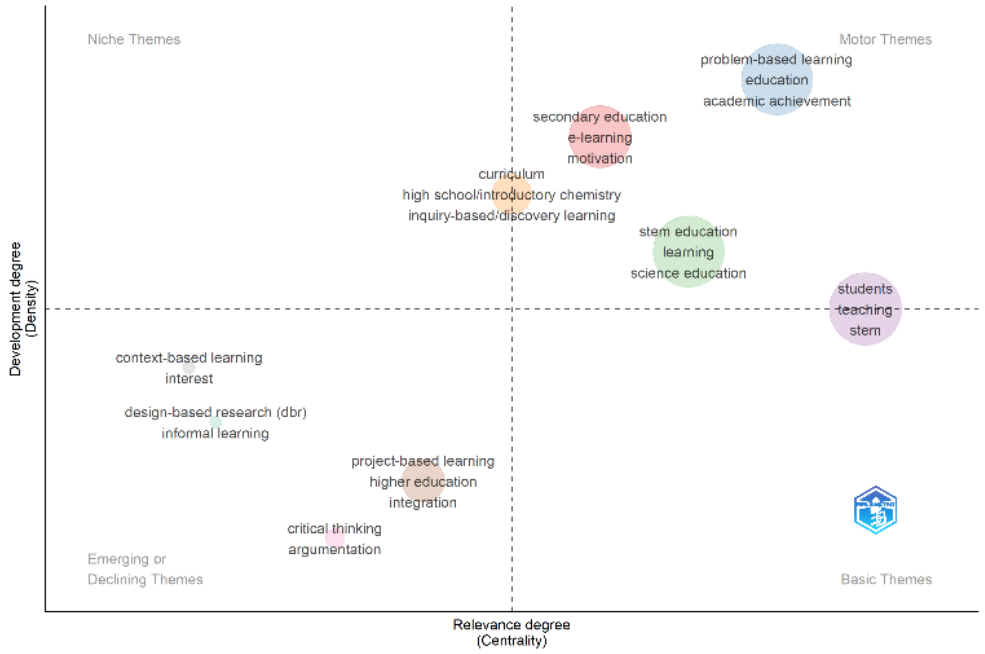

Figure 4. Thematic map.

Themes related to STEM education, learning, and science education occupy a central position with moderate density, highlighting their role as integrative connectors between pedagogical approaches and disciplinary contexts. These themes function as conceptual anchors that link PBL to broader curricular and instructional frameworks in secondary science education. Their positioning suggests continued relevance, with potential for further theoretical consolidation. In contrast, themes such as students, teaching, and STEM appear within the basic theme's quadrant. Although these themes demonstrate high centrality, their lower density indicates that they serve as foundational concepts rather than deeply specialized research strands. This positioning reflects their broad applicability across studies, while also suggesting opportunities for more focused and theoretically refined investigations within these areas.
The lower-left quadrant reveals emerging or potentially declining themes, including context-based learning, design-based research, informal learning, critical thinking, and argumentation. While these themes currently exhibit lower centrality and density, their presence indicates exploratory research trajectories that may gain prominence as methodological sophistication and theoretical integration increase. Notably, the proximity of critical thinking and argumentation to pedagogical integration suggests latent connections that remain underdeveloped within the current literature. Themes located near the boundary between quadrants, such as inquiry-based or discovery learning, curriculum, and introductory chemistry at the high school level, reflect transitional research areas. These themes demonstrate moderate relevance but limited internal cohesion, indicating that they are often incorporated as complementary approaches rather than serving as primary analytical lenses within PBL-focused studies.

3.4. *Network Visualization for Co-occurrence*

To examine the relational structure of research themes in studies on Problem-Based Learning (PBL) in secondary science education, a keyword co-occurrence network was constructed, as shown in Figure 5. This visualization captures both the frequency of keyword usage and the strength of their interconnections, allowing the identification of major thematic groupings within the literature.

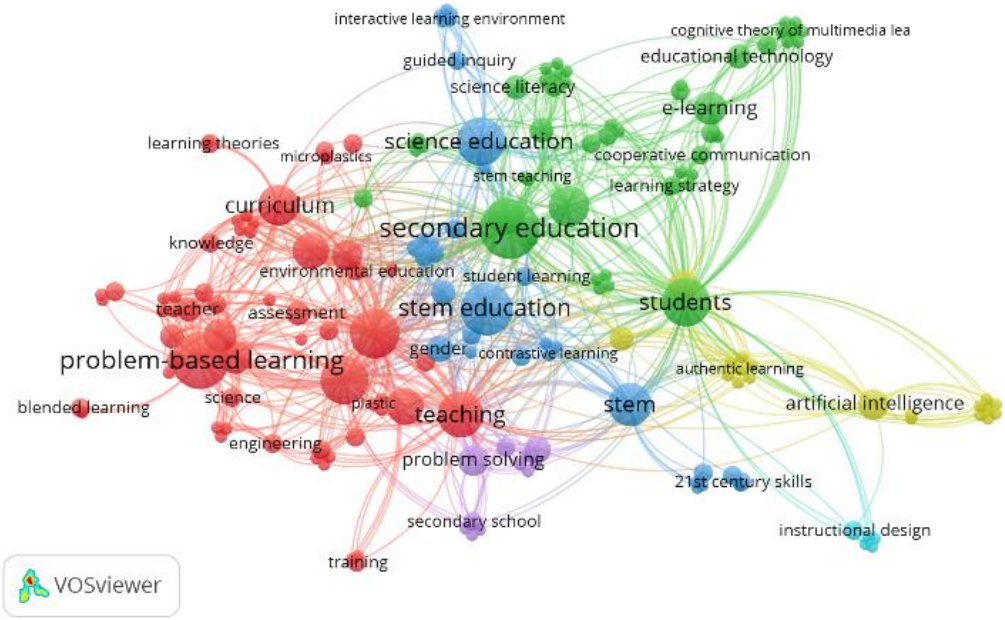

Figure 5. Network visualization for co-occurrence.

As shown in Figure 5, the network exhibits a clearly clustered structure with varying sizes and densities, indicating unequal thematic prominence across the field. Several core keywords, including problem-based learning, secondary education, students, STEM education, and science education, occupy central positions in the network. Their structural prominence indicates that these concepts function as integrative anchors linking multiple research themes. Overall, the network reveals a strong concentration of research on pedagogical and curricular issues, accompanied by additional thematic groupings related to technology-enhanced learning, interdisciplinary integration, and skill development. To clarify the internal composition of these thematic groupings, the identified clusters are summarized in Table 5 according to their relative size and representative keywords.

Table 5. Research topics on each cluster.

Cluster	Number of Items	Representative Keywords
Red	59	problem-based learning, curriculum, teaching, teacher, assessment, blended learning, engineering, science
Green	48	secondary education, students, e-learning, educational technology, cooperative learning, learning strategy, science literacy
Blue	32	STEM education, science education, STEM teaching, inquiry-based learning, guided inquiry, interactive learning environment
Yellow	19	artificial intelligence, authentic learning, digital innovation
Purple	11	problem solving, training, secondary school
Indigo	5	instructional design, 21st-century skills

As presented in Table 5, the research landscape is dominated by a large pedagogically oriented cluster centered on problem-based learning, curriculum, teaching, teacher roles, and assessment. This is followed by substantial clusters focusing on secondary education contexts, student learning, educational technology, and STEM-related inquiry approaches. Smaller clusters represent more specialized and emerging directions, particularly those related to artificial intelligence and digital innovation, problem-solving competencies, and instructional design associated with 21st-century skills.

3.5. *Overlay Visualization for Co-occurrence*

To examine the temporal evolution of research themes and identify shifts in topical emphasis over time, an overlay visualization of keyword co-occurrence was generated. As presented in Figure 6, this visualization maps keywords based on their average year of publication, using a color gradient to indicate the progression from earlier to more recent research foci within studies on PBL in secondary science education.

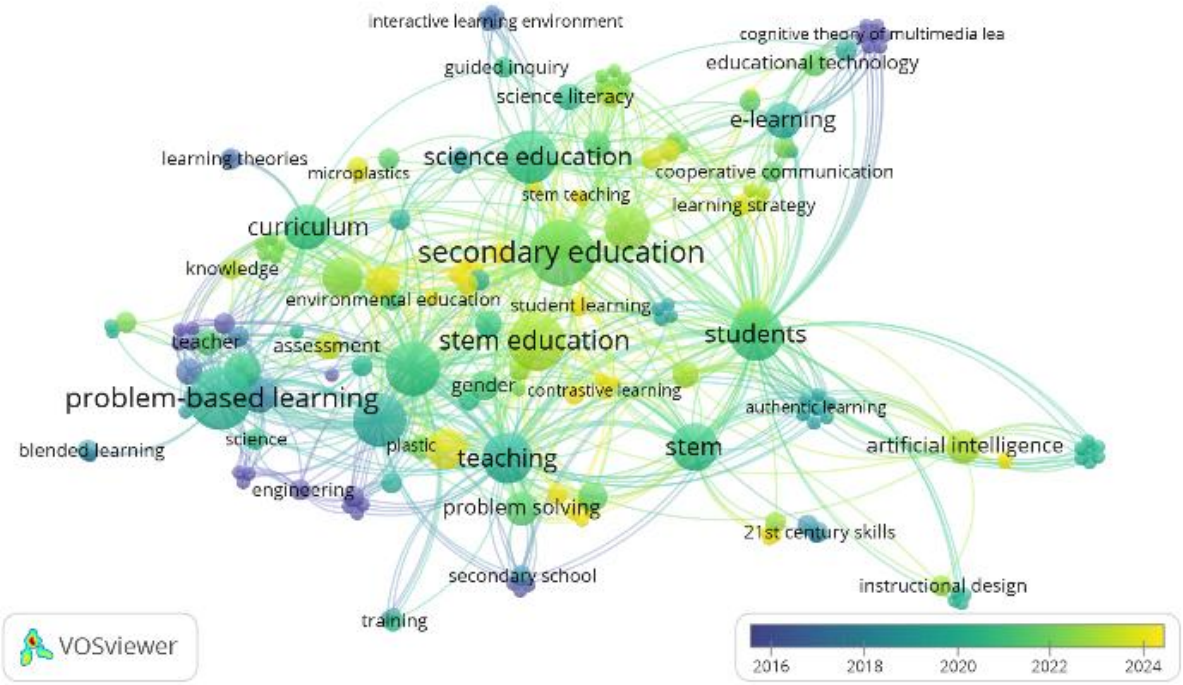

Figure 6. Overlay visualization for co-occurrence.

As illustrated in Figure 6, earlier research themes are predominantly associated with foundational pedagogical and curricular concepts, such as problem-based learning, curriculum, assessment, teachers, and blended learning, which appear in darker tones. These themes reflect the initial consolidation phase of the field, during which research primarily focused on instructional implementation, classroom practices, and pedagogical effectiveness of PBL in science-related contexts. In contrast, more recent research trends are indicated by lighter-colored nodes, highlighting a growing emphasis on technology-enhanced and future-oriented themes. Keywords such as e-learning, educational technology, artificial intelligence, 21st-century skills, authentic learning, and instructional design emerge more prominently in later years. This shift suggests an increasing integration of digital tools, intelligent systems, and competency-based frameworks into PBL-oriented secondary science education. Notably, central bridging concepts such as students, STEM education, science education, and secondary education span a broad temporal range, indicating their sustained relevance across different phases of research development. Their persistent centrality suggests that while topical emphases have evolved, the core educational context and learner-focused orientation of PBL research have remained stable.

3.6. *Density Visualization for Co-occurrence*

To assess the relative intensity and concentration of research themes within the literature, a density visualization of keyword co-occurrence was generated. Figure 7 depicts the spatial distribution of keywords based on their frequency and co-occurrence strength, where warmer color intensities indicate areas of higher thematic density in studies on PBL within secondary science education.

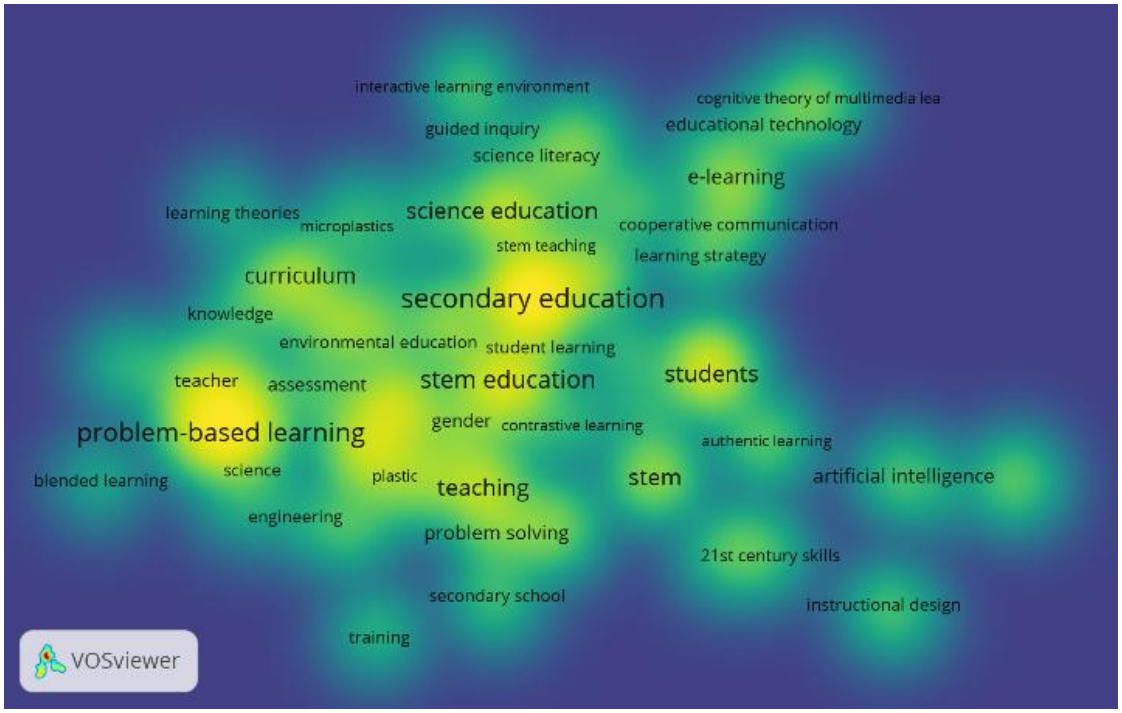

Figure 7. Density visualization for co-occurrence.

As shown in Figure 7, the highest-density region is concentrated around problem-based learning, secondary education, STEM education, science education, teaching, and students. The prominence of these keywords indicates that research in this field is heavily anchored in pedagogical practice and learner-centered contexts, with PBL serving as the core conceptual focus. The overlapping density among these themes suggests a strong and sustained integration between instructional approaches, disciplinary content, and student learning outcomes. Moderate-density areas extend toward curriculum, assessment, teachers, blended learning, and problem solving, reflecting well-established yet more specialized strands of inquiry. These themes appear frequently in conjunction with the central concepts but exhibit slightly lower intensity, indicating their role as supporting or complementary dimensions within the broader research landscape. Lower-density regions are observed around emerging and niche themes such as artificial intelligence, instructional design, 21st-century skills, authentic learning, and training. Although less prominent in terms of frequency, their distinct spatial presence suggests growing scholarly attention and the potential for future expansion, particularly in relation to digital innovation and competency-based education.

3.7. *Agenda for Future Research Direction*

The bibliometric findings reveal that research on Problem-Based Learning in secondary science education has developed a strong pedagogical core while simultaneously expanding toward technological integration, disciplinary convergence, and competency-oriented outcomes. The thematic map and co-occurrence analyses indicate a concentration of studies around instructional practices, curriculum, and student learning, alongside emerging themes related to digital technologies, artificial intelligence, and future skills. However, the overlay and density visualizations suggest that several promising directions remain underexplored or unevenly developed. Building on these patterns, future research can be strategically oriented toward deepening theoretical coherence, expanding methodological diversity, and addressing emerging educational challenges. Table 6 synthesizes key research streams derived from the observed thematic structure and proposes targeted future research questions to guide subsequent investigations.

Table 6. Future research questions

Research Stream	Focus	Future Research Questions
Core Pedagogical Design of PBL	Design characteristics of effective PBL in secondary science classrooms	• Which problem characteristics (ill-structured, interdisciplinary, real-world) most strongly influence conceptual understanding in secondary science PBL? • How does the level of scaffolding affect students' autonomy and depth of inquiry during PBL implementation?
	Alignment between PBL pedagogy and assessment practices	• What forms of assessment most accurately capture learning processes and outcomes in PBL-based science instruction? • How can assessment be designed to support learning progression rather than merely evaluate final products?
Learners and Learning Processes in PBL	Student engagement and participation patterns	• How do students' learning strategies and motivation interact with PBL task design in secondary science contexts?
	Equity, gender, and participation in PBL environments	• What patterns of participation emerge among different student groups during collaborative PBL activities? • How can PBL be structured to reduce participation gaps without simplifying cognitive demands?
	Development of problem-solving and reasoning skills	Which aspects of PBL most effectively support the development of scientific reasoning and problem-solving skills?
STEM and Disciplinary Integration	PBL as a bridge across STEM disciplines	How does PBL facilitate conceptual coherence across science, technology, engineering, and mathematics at the secondary level?
	Integration of inquiry-based and guided inquiry approaches	• In what ways do hybrid inquiry–PBL models reshape students' engagement with scientific practices? • When does guided inquiry provide added value within PBL-oriented STEM learning?

3.8. *Discussion*

This study systematically mapped the development, structure, and thematic evolution of research on Problem-Based Learning (PBL) in secondary science education. The bibliometric results address these objectives by showing trends in publication growth, international collaboration, and thematic interconnections, providing a clearer picture of the field's intellectual structure. The steady increase in publications over the last decade confirms that PBL has become a central pedagogical focus, reflecting broader educational calls for learner-centered and inquiry-oriented approaches. The dominance of pedagogical and curricular themes, evident in co-occurrence and thematic analyses, suggests that researchers are primarily concerned with how PBL can be effectively designed and implemented in classroom settings. This aligns with findings by [34], who reported that instructional scaffolding, teacher facilitation, and curriculum alignment are key factors for PBL success. The bibliometric approach shows that these concerns are interconnected, forming the core intellectual structure of the field.

The identification of clusters emphasizing secondary education contexts and STEM-oriented inquiry indicates a shift from traditional higher education settings toward secondary science. This trend is highlighted by [35], who emphasized that problem-centered inquiry supports integrated scientific reasoning and real-world problem-solving skills. It suggests that PBL increasingly functions as a bridge between disciplinary knowledge and authentic application in secondary STEM education. Emerging clusters related to artificial intelligence, digital innovation, and 21st-century skills reveal an expanding thematic scope. Overlay visualizations suggest that technology-oriented research in PBL, such as learning analytics and intelligent tutoring systems, remains nascent. These findings indicate a gap between technological potential and widespread pedagogical adoption, highlighting opportunities for future studies on digital integration in PBL.

Geographical and institutional analyses provide further context. Research productivity remains concentrated in a few countries, yet increasing multi-country collaborations suggest a gradual internationalization of PBL research. This pattern is consistent with observations by [36], who noted that educational innovations often originate regionally before spreading globally. Variations in

collaboration intensity may explain differences in thematic emphasis, particularly in technology integration and curriculum reform [37–41]. Overall, the results demonstrate that PBL research in secondary science education is evolving in a multidimensional and interconnected manner. The findings situate pedagogical, technological, and disciplinary themes within a unified framework, revealing both established and emerging trends. The relatively small size of technology-focused clusters highlights a gap for future research, particularly regarding how digital tools can complement traditional PBL strategies to enhance student engagement and learning outcomes.

Based on these findings, several recommendations can be proposed to advance future research and practice. First, there is a need for more integrative studies that explicitly combine pedagogical design with emerging technologies, ensuring that digital tools such as artificial intelligence and learning analytics are not only explored conceptually but also implemented and evaluated in authentic classroom contexts. Second, future research should focus on developing and validating context-sensitive PBL models tailored to secondary science education, particularly in diverse socio-cultural and resource-constrained settings, to enhance scalability and inclusivity. Third, strengthening international and cross-institutional collaborations is essential to promote knowledge exchange and reduce regional disparities in research productivity and innovation. Finally, researchers are encouraged to explore underrepresented areas, such as the long-term impact of PBL on students' sustainability awareness, higher-order thinking skills, and interdisciplinary competencies, as well as the role of teacher professional development in sustaining effective PBL implementation. Collectively, these directions can contribute to a more comprehensive and forward-looking development of PBL research in secondary science education.

4. Conclusion

This study provides a comprehensive bibliometric overview of research on Problem-Based Learning in secondary science education over the 2015–2025 period. The findings reveal a steadily growing body of literature characterized by strong concentration on pedagogical and curricular dimensions, with Problem-Based Learning positioned as the central conceptual anchor. Network and thematic analyses indicate that PBL is most frequently integrated with secondary education contexts, STEM-oriented frameworks, and student-centered learning approaches, while emerging themes related to digital technologies, artificial intelligence, and future-oriented competencies remain less structurally central. Overall, the research landscape reflects both consolidation around established instructional practices and gradual diversification toward interdisciplinary and technology-enhanced learning paradigms.

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