

Review Article

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Problem-Based Learning in Mathematics Education: A Bibliometric Analysis of Key Trends and Future Directions in the Last Decade

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Abstract

Background/purpose. This study aims to explore the research trends, influential contributors, and thematic developments in PBL within the context of school-level mathematics education over the period 2015–2024.

Materials/methods. A bibliometric analysis was conducted on 430 documents indexed in the Scopus database. The analysis employed R-Biblioshiny and VOSviewer tools to examine publication patterns, author and institutional contributions, keyword co-occurrence, and thematic clustering.

Results. The findings reveal a significant increase in PBL-related publications over the past decade. Indonesia, particularly Universitas Negeri Semarang and Universitas Pendidikan Indonesia, emerged as leading contributors. Capraro M.M., Arnawa I.M., and Capraro R.M. were identified as the most prolific authors, while Han and Laforce had the highest citation impact. The Journal of Physics: Conference Series and AIP Conference Proceedings were the most frequently cited publication outlets. Three major themes were identified: the development of critical thinking skills, the integration of PBL with STEM education, and the incorporation of educational technologies.

Conclusion. This study maps the growth of PBL research in mathematics education and highlights future directions, including AI and transdisciplinary approaches. These insights support the development of more innovative and technology-based practices.

1. Introduction

Problem-Based Learning (PBL) has been widely recognized as an innovative and practical approach in mathematics education, promoting a deeper understanding of mathematical concepts among students. This pedagogical model engages students in solving authentic and relevant problems that foster critical thinking, collaboration, and problem-solving skills (Arifin et al., 2020; Dorimana et al., 2022). Within the context of mathematics, PBL not only emphasizes the practical application of concepts but also enhances students' ability to address complex problems that lack immediate solutions (Izzati, 2021). Increasingly implemented in school settings, PBL boosts student motivation and learning outcomes by connecting mathematical theories to real-world contexts (Arifin et al., 2020).

PBL has shown considerable potential in school mathematics education. Numerous studies have demonstrated its effectiveness in improving critical thinking, problem-solving, and mathematical literacy (Junianto & Wijaya, 2019; Magdalena et al., 2023; Nisa' et al., 2023). Additionally, PBL positively influences students' motivation, interest, and attitudes toward mathematics (Meke et al., 2019; Nisa' et al., 2023). However, its implementation still faces several challenges, particularly in lesson planning, time management, and facilitating student-centered learning (Nurlaily et al., 2019). Despite a growing body of literature on the use of PBL in education, there remains a gap in comprehensive analyses that chart the development of research trends specifically within the domain of school mathematics education (Magaji et al., 2024; Zhang et al., 2022).

Several studies have attempted to review PBL practices in mathematics education. For instance, Abushkin et al. (2018) conducted an evaluative study focusing on secondary school teachers' perceptions of PBL in Mordovia, addressing implementation challenges without examining broader research trends. Ng and Fergusson (2020) explored project-based learning and design thinking within STEAM programs in Australia to enhance female participation in mathematics. However, their emphasis was on gender empowerment and not PBL itself. Darmawansah et al. (2023) systematically reviewed robotics-based STEM (R-STEM) education, identifying PBL as a frequently used approach. However, their focus was limited to technological integration without a bibliometric dimension. Likewise, Aba-Oli et al. (2024) reviewed 14 studies on PBL in secondary school mathematics, yet did not employ a bibliometric approach to assess research patterns comprehensively.

These gaps underscore the need for a systematic bibliometric analysis to map the evolution and direction of PBL research in school mathematics education. The present study addresses this need by employing a bibliometric approach to analyze research trends in the field over the past decade. By examining publication patterns, dominant themes, author networks, and emerging research directions, this study provides a macro-level overview of the scholarly landscape surrounding PBL in mathematics education. This study aims to offer comprehensive insights into publication trends, identify prevailing themes, and explore future avenues for inquiry into PBL practices in school-based mathematics learning. To guide this investigation, the study is structured around the following research questions:

1. What are the main trends in the application of PBL in mathematics learning?
2. How do countries, institutions, and authors contribute to the development of this field?
3. What are the key research themes in the current practice of PBL in school mathematics learning?
4. What potential themes in PBL practices within mathematics learning warrant future research?

2. Literature Review

PBL is a pedagogical approach that centers on real-world problems as the primary stimulus for learning. In mathematics education, PBL enables students to develop problem-solving skills by applying mathematical concepts to address complex, often ill-structured problems (Aba-Oli et al., 2024). Rooted in the constructivist theories of Piaget and Vygotsky, PBL emphasizes the active construction of knowledge through direct experience within social and cultural contexts (Smith et al., 2022). This approach fosters student collaboration, encourages independent inquiry, and guides learners in developing practical solutions to contextualized problems (Rehman et al., 2024). Within mathematics classrooms, PBL has the potential to enhance student engagement, promote critical thinking, and increase motivation by bridging abstract mathematical theories with real-life applications (Wiradnyana et al., 2024). Furthermore, PBL supports the development of essential 21st-century skills such as teamwork and communication, which are increasingly valued in professional and academic settings.

Implementing PBL in school-based mathematics instruction faces several challenges despite its pedagogical strengths. Many educators struggle to facilitate group dynamics, maintain active student participation, and deliver meaningful feedback (Al Said et al., 2019; Nurlaily et al., 2019). Moreover, the variability in research findings suggests that the effectiveness of PBL is not uniformly realized across different educational contexts (Chen et al., 2021). As the body of literature on PBL continues to expand, especially in school mathematics, the boundaries between research areas have become increasingly diffuse, making it challenging to delineate clear directions for future inquiry (Nurlaily et al., 2019; Rézio et al., 2022; Sukasno et al., 2018). These issues underscore the need for a more systematic and comprehensive examination of current research trends to better understand the impact and optimization of PBL in mathematics education.

3. Methodology

3.1. Research Design Data Collection and Source Identification

This study adopts a bibliometric approach to systematically analyze the development of research on Problem-Based Learning (PBL) in school-level mathematics education from 2015 to 2024. Bibliometric analysis provides a quantitative method for evaluating patterns in scholarly publications, enabling the identification of research trends, influential works, knowledge gaps, and collaboration networks across institutions and countries (Guo et al., 2019; Putri et al., 2023). By employing bibliometric tools such as Biblioshiny for R and VOSviewer, this study visualizes keyword co-occurrences, author networks, and thematic clusters. This methodological lens enables an in-depth examination of how PBL in mathematics education has evolved over the past decade, identifying emerging themes and future research directions (Nasrum et al., 2025; Salido, Sugiman, et al., 2024).

3.2. Data Collection and Source Identification

The bibliometric data for this study were obtained from the Scopus database, which was selected for its extensive coverage of peer-reviewed literature and its structured, high-quality metadata that facilitate comprehensive bibliometric analysis (Nasrum et al., 2025). A systematic search was performed using the following keywords: (“problem-based learning” OR PBL OR “problem-based learning”) AND math AND learning AND school**. The search was restricted to publications from 2015 to 2024 to ensure that the analysis captured a full decade of recent scholarly developments in the field. The inclusion criteria were limited to two types of documents: journal articles and conference proceedings, selected to maintain academic rigor and relevance. No language restrictions are applied to cover the entire metadata related to the theme over the last decade. In addition, non-peer-reviewed materials, including editorials, book reviews, theses, and other forms of grey

literature, were not considered. Applying these criteria resulted in the identification of 430 relevant documents, which were included in the final dataset for analysis.

To enhance data reliability, metadata exported from Scopus were refined using OpenRefine, an open-source tool designed for data cleaning and transformation. OpenRefine enables the detection and elimination of duplicate entries, the correction of typographical inconsistencies, and the standardization of author names, institution identifiers, and keyword tags (Verborgh & Wilde, 2013). This step was crucial in mitigating the risk of data redundancy and analytical distortion, thereby ensuring that the bibliometric results accurately reflect the structure and content of the original dataset.

3.3. Data Analysis

The cleaned dataset was analyzed using Biblioshiny, a web interface for the Bibliometrix R package, which supports statistical and descriptive analyses of bibliographic data (Passas, 2024). Biblioshiny facilitated the computation of publication frequencies, citation metrics, and author productivity, as well as the identification of leading countries, institutions, and journals contributing to the field.

Additionally, VOSviewer was employed to construct visual maps representing the co-occurrence of keywords, co-authorship networks, and institutional collaboration patterns. These visualizations enabled the identification of thematic clusters and intellectual structures within the PBL in the mathematics education research landscape. VOSviewer's strength in constructing distance-based maps provided insights into the centrality and density of research topics, revealing both dominant and emerging themes in the literature.

The results obtained from both tools were interpreted in light of the study's research objectives. The bibliometric indicators were contextualized within existing theoretical frameworks on instructional design and mathematics education to facilitate a meaningful discussion of patterns, gaps, and directions in the field. This approach enabled the study not only to map the evolution of PBL research over time but also to position the findings within broader scholarly conversations, thereby enhancing the interpretative depth and academic contribution of the research.

4. Results

4.1. Key Trends in the Implementation of PBL in Mathematics Education

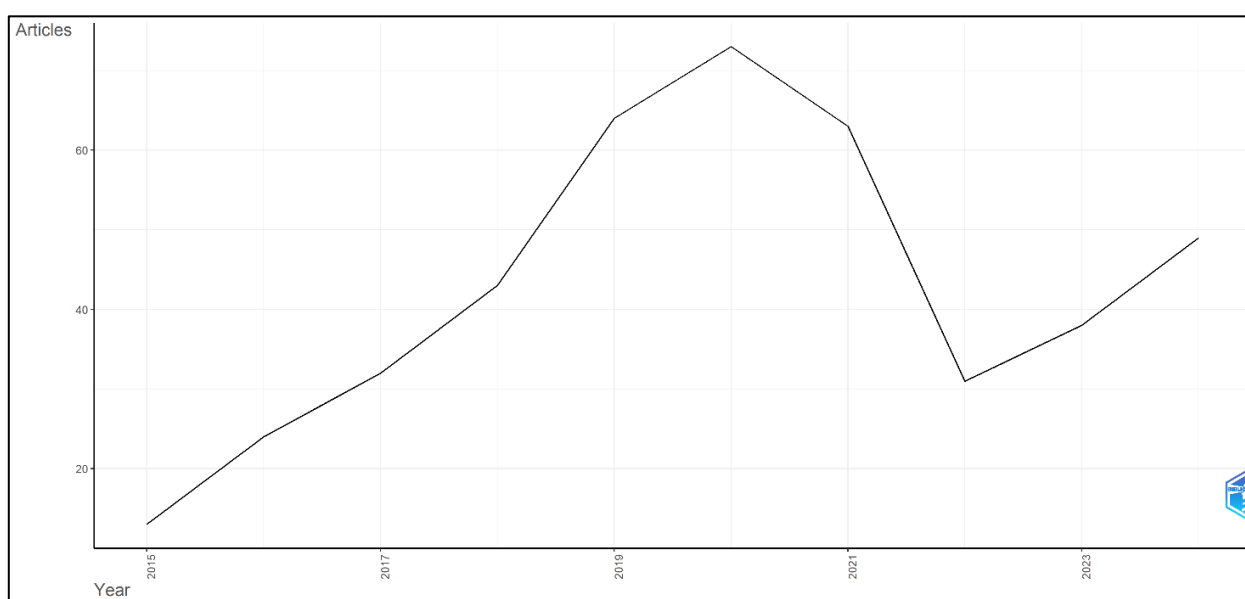


Figure 1. Publication Trends Annually From 2015 to 2024

Figure 1 presents the annual scientific production of PBL in mathematics education from 2015 to 2024. The trend shows a steady increase in publications from 2015 (about 12 articles) to reaching its peak in 2020 with more than 70 articles. This growth reflects the increasing interest of academics in implementing the PBL approach in mathematics education during this period. However, a notable decline occurred in 2021, with publications dropping significantly below 30. After 2021, production recovered gradually, reaching around 50 articles by 2024, which indicates a recovery in academic focus on this topic.

4.2. Contributions of Countries, Institutions, Journal Source and Authors to the Field

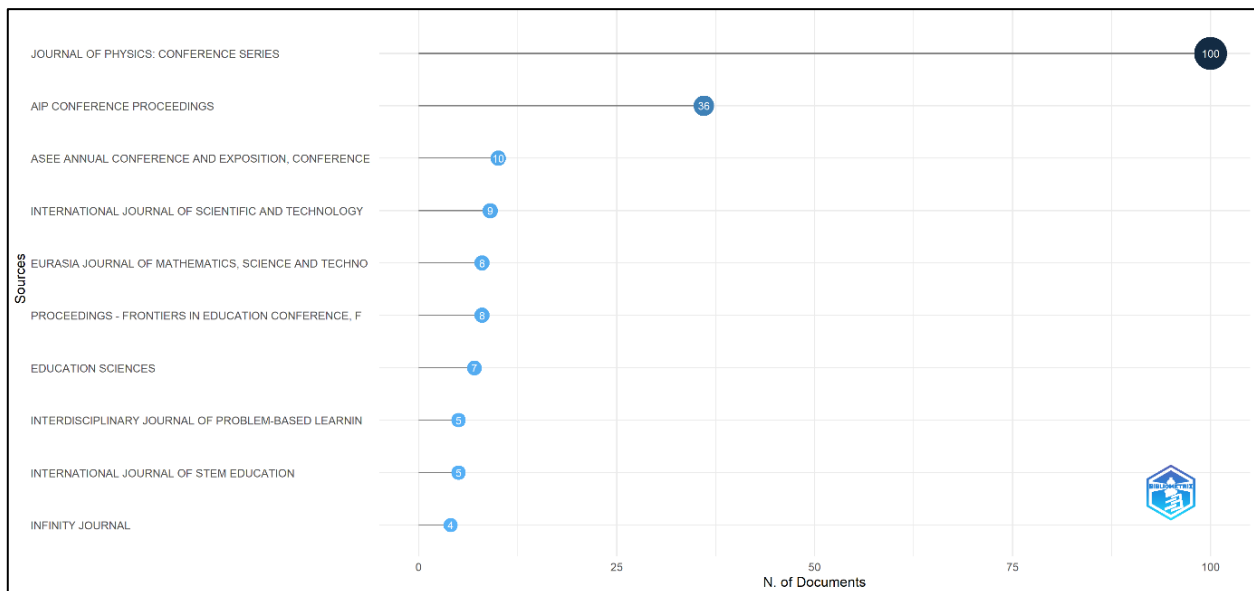


Figure 2. Top 10 Relevant Journal Sources in Publications

Figure 2 shows the most relevant sources contributing to the literature on PBL in school mathematics education. "Journal of Physics: Conference Series" emerged as the most prolific source with 100 publications, followed by the "AIP Conference Proceedings" with 36 publications. Other notable sources include the "ASEE Annual Conference and Exposition, Conference" (10 publications), "International Journal of Scientific and Technology Research" (9), "Eurasia Journal of Mathematics, Science and Technology Education" (8), and the "Proceedings - Frontiers in Education Conference, FIE" (8). Additional journals such as "Education Sciences" (7), "Interdisciplinary Journal of Problem-Based Learning" (5), "International Journal of STEM Education" (5), and "INFINITY Journal" (4) also made significant contributions to this theme, indicating a diverse distribution pattern. Furthermore, the results of the analysis of productive authors in this field of study are presented in Figure 3.

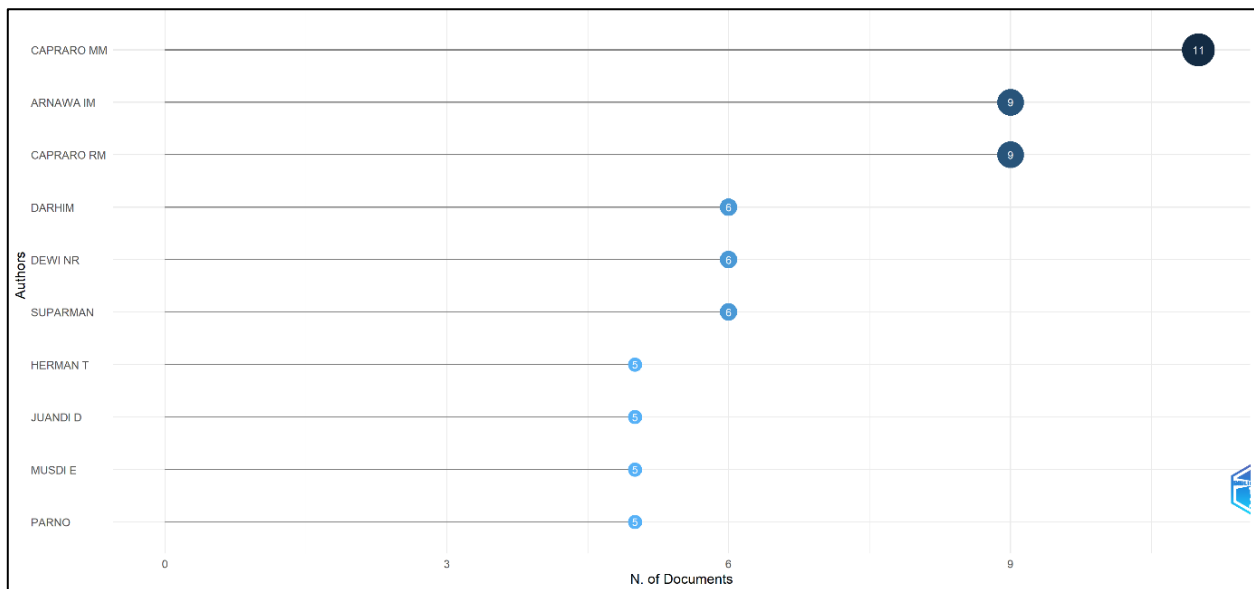


Figure 3. Top 10 Prolific Authors in Publications

Figure 3 shows the ten most relevant authors in the PBL study on mathematics education based on the number of publications. The author with the highest contribution is Capraro MM, who has 11 documents, followed by Arnawa IM and Capraro RM, who have nine publications. Other authors with significant contributions, as many as six documents, include Darhim, Dewi NR, and Suparman. Meanwhile, Herman T, Juandi D, Musdi E, and Parno each were recorded as having five publications. The diversity of these authors shows that an active academic community from various backgrounds consistently publishes scientific papers on the implementation of PBL in the context of mathematics education. Meanwhile, the 10 authors who have had an impact in publications on this theme are presented in Figure 4.

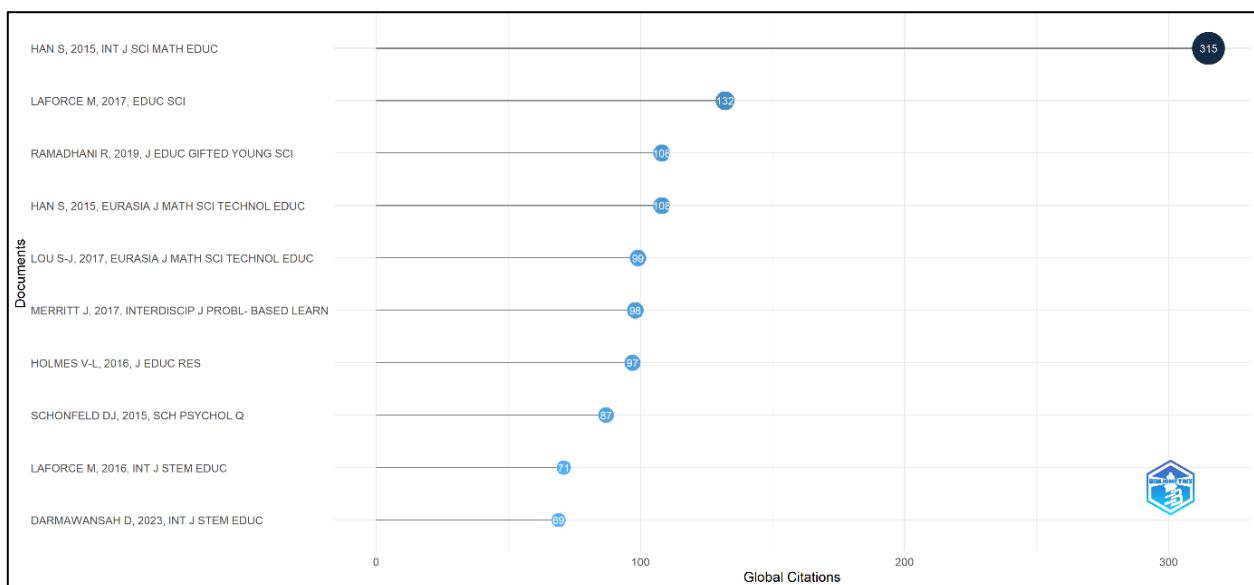


Figure 4. Top 10 Authors Have an Impact on the Publication

Figure 4 shows the ten most cited documents globally in the study of PBL in mathematics education. Han (2015) wrote the most influential article in the International Journal of Science and Mathematics Education with a total of 315 citations. It was followed by LaForce (2017) in Education Sciences with 132 citations, as well as articles by Ramadhani (2019) and Han (2015) in the Eurasia Journal of Mathematics, Science and Technology Education, which collected 108 citations each. Other documents that also stand out are the works of Lou (2017), Merritt (2017), and Holmes (2016),

with a total of 99 citations, 98 citations, and 97 citations, respectively. Furthermore, Schonfeld (2015) and Laforce (2016) obtained 87 and 71 citations, respectively. Recent work by Darmawansah (2023) has also shown significant influence, with 69 citations in a relatively short time. Meanwhile, the top 10 institutions that are relevant and actively publishing in this field of study are presented in Figure 5.

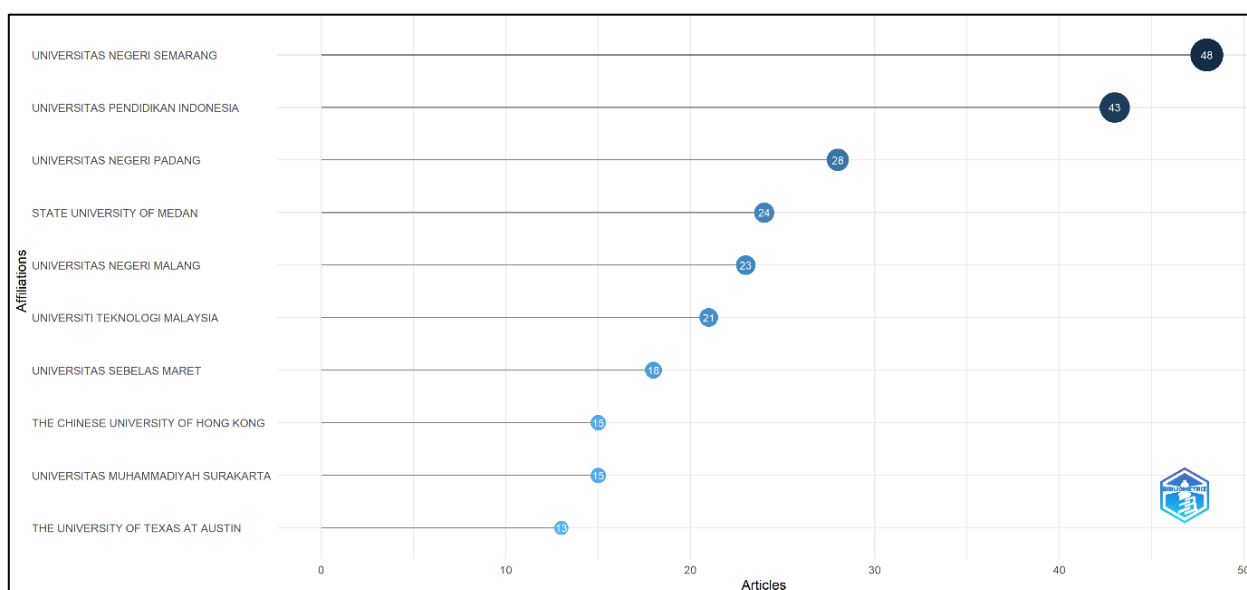


Figure 5. Top 10 Relevant Institutions in Publications

Figure 5 shows the analysis results using the R-Biblioshiny software, which describes the 10 institutions with the most significant number of publications. Universitas Negeri Semarang ranked first with 48 documents, followed by Universitas Pendidikan Indonesia (43 documents) and Universitas Negeri Padang (26 documents). Furthermore, the State University of Medan and Universitas Negeri Malang contributed 24 and 23 documents, respectively. Other institutions included in this list are Universiti Teknologi Malaysia (21 documents), Universitas Sebelas Maret (18 documents), The Chinese University of Hong Kong (15 documents), Universitas Muhammadiyah Surakarta (15 documents), and The University of Texas at Austin (13 documents). Furthermore, the analysis results of the countries of origin of the correspondents are presented in Figure 6.

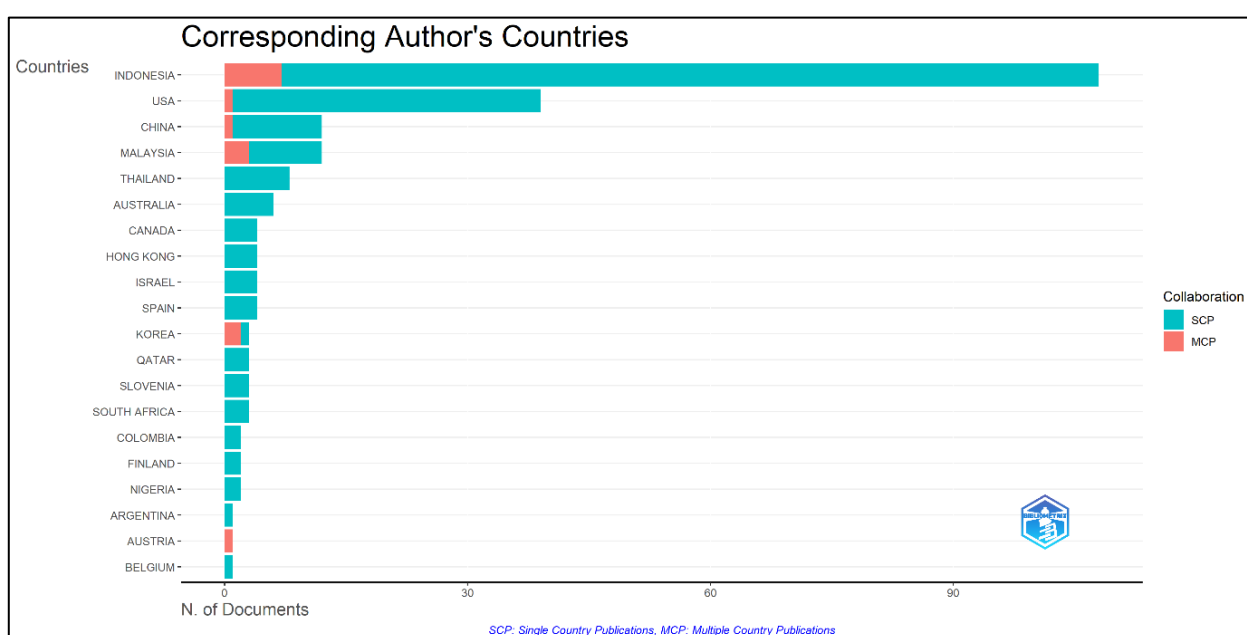


Figure 6. Top 20 Countries of Origin Corresponding Author

Figure 6 presents data on the distribution of countries of origin of the corresponding authors. Indonesia dominated the contribution with 108 documents (25.1%), consisting of 101 domestic publications (Single Country Publications (SCP) and seven cross-border collaborative publications (Multiple Country Publications (MCP), which reflected 6.5% of Indonesia's total articles. The following country is the United States, with 39 documents (9.1%), almost all as single country publications (SCP = 38; MCP = 1). China donated 12 documents, most SCPs (11 documents), and only one MCP. Malaysia tends to collaborate more than other Asian countries, with 3 out of 12 documents (25%) resulting from international collaboration. Several other countries, such as Thailand, Australia, Canada, Hong Kong, and Israel, contributed to the SCP, showing the lack of international collaboration. The countries with the highest proportion of MCP are Austria (100%) and Korea (66.7%).

4.3. Central Themes in PBL Practice in Mathematics Education

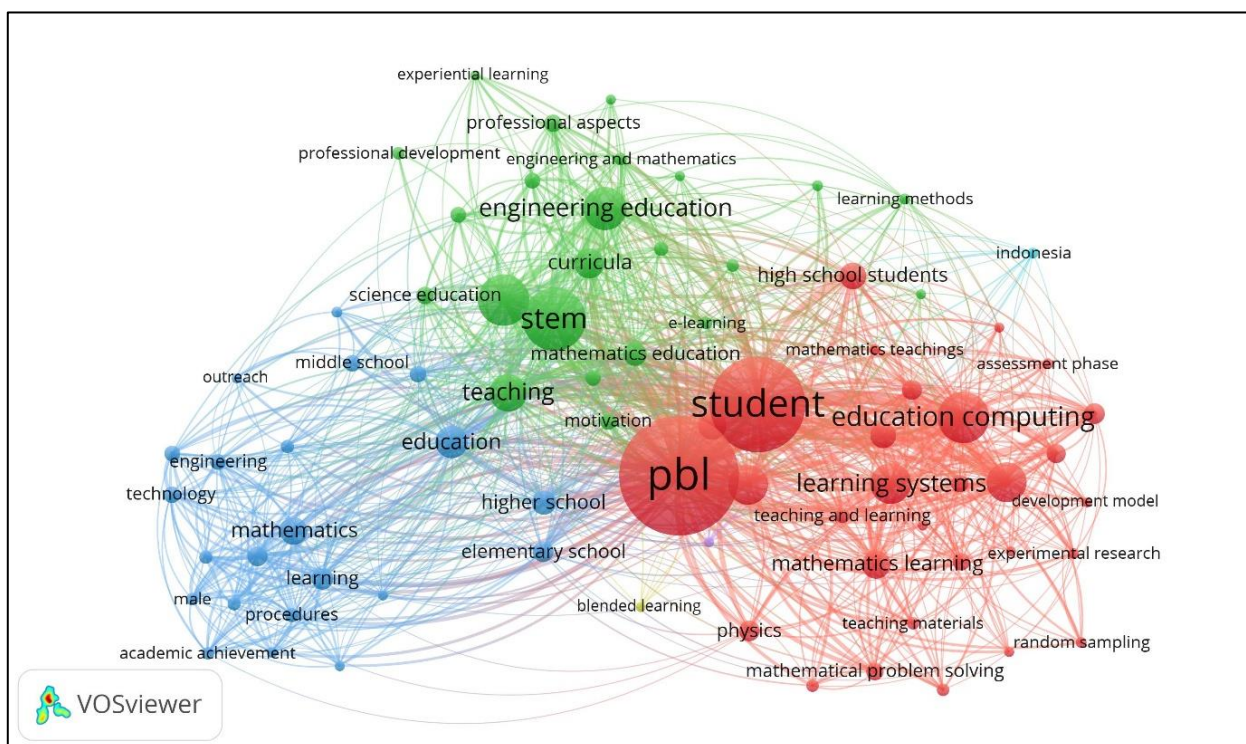


Figure 7. Co-occurrence Network Visualization

The results of the keyword linkage analysis using VOSviewer, as shown in Figure 7, identify six main clusters that represent research themes in the field of education, especially related to the PBL approach in mathematics learning. The first cluster (red) was the most dominant, covering 30 keywords such as “pbl”, “student”, “education computing”, “mathematics learning”, “learning systems”, and “critical thinking”. This cluster shows that the primary focus of the research is on the effectiveness of the application of Problem-Based Learning in improving the quality of mathematics learning, especially at the secondary education level. The second cluster (green) consists of 23 keywords such as “stem”, “engineering education”, “project-based learning”, “curricula”, and “science education”, which describes the great concern for the integration of science, technology, engineering, and mathematics (STEM)-based education, as well as the implementation of project-based curriculum as the primary pedagogical strategy.

The third cluster (dark blue) comprises 22 keywords covering “education”, “mathematics”, “human”, “middle school”, “higher school”, “elementary school”, and “technology”. This cluster emphasizes disseminating research topics at various levels of formal education and using technology to support active learning. Meanwhile, there are three minor clusters: the fourth cluster (yellow) with

one keyword, namely “blended learning”, the fifth cluster (purple) with “mathematical thinking”, and the sixth cluster (light blue), which contains the keyword “Indonesia”. These three clusters indicate a more specific research interest in learning approaches that combine online and offline methods, in-depth mathematical thinking, and the geographical context of research that shows a significant contribution from studies conducted in Indonesia.

4.4. Future Research Directions in PBL for Mathematics Education

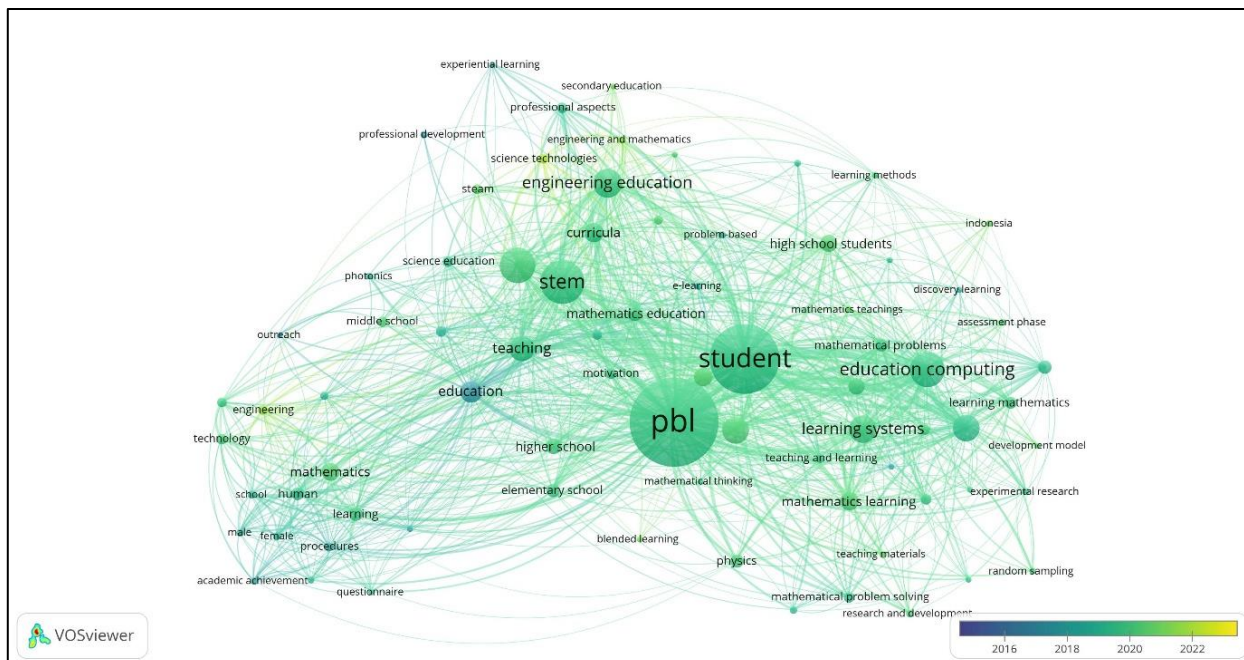


Figure 8. Co-occurrence Overlay Visualization

Figure 1Figure 8 shows the results of an overlay visualization analysis using VOSviewer that shows the temporal distribution of the PBL approach theme in mathematics learning. The colors in this visualization represent the average year of occurrence of each keyword, with color gradations ranging from dark blue (older, around 2016) to light yellow (newer, around 2022) (Salido, Haryanto, et al., 2024). This visualization shows that keywords with lighter colors tend to show the intensity of publication in recent years. Keywords such as “science technologies”, “engineering”, “engineering and mathematics”, “secondary education”, “steam”, and “critical thinking” appear to dominate yellowish regions, indicating that these themes are relatively new and of concern in cutting-edge research, especially around 2022. On the other hand, keywords such as “mathematics”, “learning”, and “education” that appear in green or blue indicate that these themes were already an early concern and remain relevant today.

5. Discussion

5.1. Key Trends in the Implementation of PBL in Mathematics Education

The analysis of publication trends reveals a significant increase in research interest in PBL in mathematics education up to 2020. However, this upward trend experienced a sharp decline in 2021, which can be attributed to the widespread disruptions caused by the COVID-19 pandemic. Sohrabi et al. (2021) reported that the pandemic significantly affected academic productivity and led to a reorientation of research priorities across various disciplines. Encouragingly, a recovery in publication volume began in 2022, aligning with broader educational research trends that explore the adaptability of PBL to online and hybrid learning environments (Caroni & Nikoulina, 2021; Jadhav et al., 2023). These findings emphasize the growing relevance of PBL in responding to educational

challenges and demonstrate how global events can shape the trajectory of research in specific pedagogical areas.

5.2. Contributions of Countries, Institutions, and Authors to the Field

The study highlights that conference proceedings dominate the primary publication outlet for PBL research in mathematics learning. The Journal of Physics: Conference Series and AIP Conference Proceedings are the most frequently used publication platforms in this domain. This trend suggests that research in this area is often exploratory and presented in multidisciplinary scientific forums, reflecting the innovative and experimental nature of PBL implementation. In addition to these proceedings, several academic journals, such as the International Journal of Scientific and Technology Research, Eurasia Journal of Mathematics, Science and Technology Education, and the Interdisciplinary Journal of Problem-Based Learning, have also contributed significantly. Other sources like the International Journal of STEM Education and INFINITY Journal—though less frequent—further demonstrate the cross-disciplinary engagement with PBL in educational research. This diversity of publication venues indicates that the academic community views PBL as a pedagogical method and a research-worthy innovation with broad applicability.

At the author level, figures such as Capraro M.M., Arnawa, and Capraro R.M. emerge as the most prolific contributors to PBL research in mathematics education. In particular, the active participation of Indonesian scholars such as Arnawa, Darhim, Dewi, and Juandi underscores the country's strong academic involvement in developing PBL at the primary and secondary education levels. This pattern reflects the growing recognition of PBL as a viable instructional strategy across various education systems and cultural contexts. The contributions of these authors also indicate the formation of a dynamic and increasingly collaborative research ecosystem in mathematics education, particularly within Indonesia (Dorimana et al., 2022). Such collaboration enriches the literature and enhances the legitimacy and sustainability of PBL as a research field.

Regarding citation impact, authors such as Han and Capraro have significantly influenced two pivotal publications released in 2015. One of these studies explored the variation in learning outcomes associated with STEM-based PBL. At the same time, the other, authored by Han, Yalvac, and Capraro, examined teacher perceptions and implementation practices, thus offering practical insights into the pedagogical challenges of PBL. Laforce is another influential figure, having contributed research on student motivation and interest in STEM careers and frameworks for inclusive STEM education. Other impactful authors include Ramadhani R., who investigated the integration of flipped-PBL models using Google Classroom, and Lou, who focused on fostering creativity through STEM-based project learning. Merritt et al., Holmes & Hwang, and Schonfeld et al. have further enriched the theoretical and practical foundations of PBL, especially concerning K–8 education, secondary mathematics, and social-emotional learning, respectively. These findings illustrate that academic influence in the field stems from the number of publications and the thematic and conceptual significance of the contributions.

Institutionally, Indonesian universities dominate the landscape of PBL research in mathematics education. Universitas Negeri Semarang, Universitas Pendidikan Indonesia, and Universitas Negeri Padang rank among the most productive institutions in this field. Their prominence suggests the existence of strong research programs supported by national research agendas and institutional funding. In addition to domestic institutions, international universities such as The Chinese University of Hong Kong and The University of Texas at Austin have also contributed, albeit on a smaller scale. Meanwhile, Universiti Teknologi Malaysia represents active regional collaboration efforts in Southeast Asia. The presence of diverse institutions indicates the increasing global acknowledgement of PBL as a promising approach to mathematics instruction.

From a national perspective, Indonesia is the leading contributor to the literature on PBL in mathematics education. This finding reflects the country's commitment to promoting active, student-centered learning approaches in alignment with national education reforms (Amiruddin et al., 2023). The United States ranks second, followed by China and Malaysia. Malaysia records many multi-country publications (MCPs), signaling robust international research collaboration. The emergence of contributors from other parts of Southeast Asia and North America further emphasizes the global scope and appeal of PBL. These patterns confirm that PBL has evolved into a transnational research theme with significant potential to enhance the quality of mathematics learning across diverse educational contexts worldwide.

5.3. Central Themes in PBL Practice in Mathematics Education

The visual mapping of keywords indicates that PBL approach is a central theme in the analyzed literature. The first cluster (red) significantly focuses on implementing PBL in secondary education, particularly enhancing critical thinking skills, mathematical problem-solving abilities, and technology-enhanced learning systems. These findings align with previous studies asserting that PBL can improve students' motivation and higher-order thinking skills in mathematics learning (Arifin et al., 2020; Dorimana et al., 2022). Furthermore, integrating technology—such as educational computing—within the PBL framework has emerged as a key concern in aligning instruction with 21st-century educational demands, especially amidst the ongoing digitalization of learning environments (Wijayanto et al., 2023).

The second cluster (green) reveals a strong connection between project-based learning approaches and the advancement of STEM education. Keywords such as engineering education, science education, and curriculum suggest that research is also directed toward developing cross-disciplinary curricula that foster practical and integrative learning. Through experiential learning, project-based curricula have increased student engagement and conceptual understanding of STEM subjects (Attard et al., 2021; Karan & Brown, 2022). The third cluster (dark blue) encompasses themes across various educational levels—from primary to secondary—indicating the generalization of innovative instructional strategies across contexts. This finding is consistent with prior research emphasizing that active learning strategies significantly enhance mathematics learning outcomes at all educational stages (Lopez-Caudana et al., 2020; Žakelj et al., 2024).

Minor clusters, such as blended learning (yellow) and mathematical thinking (purple), represent more focused research directions, particularly on specific pedagogical models and the development of advanced cognitive skills. Blended learning has gained attention as a flexible instructional solution that maintains student interaction and learning quality (Prasetya et al., 2020). Additionally, the emergence of the keyword Indonesian as a standalone cluster (light blue) reflects a significant local context in the dataset. This finding demonstrates the prominent academic contribution of Indonesian institutions and underscores the rapid growth of mathematics education research at the national level.

5.4. Future Research Directions in PBL for Mathematics Education

Overlay visualization results indicate that research topics in mathematics education are continually evolving in response to emerging educational demands. Around 2016, the focus of PBL-related studies in mathematics was closely associated with integrating STEM education and innovative instructional strategies. The presence of keywords such as science technologies, engineering, and STEAM evidences this. These trends reflect a paradigm shift in education from theoretical instruction toward more interdisciplinary and application-oriented approaches. As Inpinat and Inprasit (2016) noted, integrating PBL with STEM concepts has enhanced students' mathematical understanding more effectively than traditional methods.

Implementing STEM education in mathematics learning has significantly influenced students' motivation and comprehension, allowing them to perceive real-world connections between mathematics, technology, and engineering (Goos et al., 2023). In this regard, PBL-STEM integration prepares students to meet global challenges by equipping them with broad, applicable skills. This hybrid approach offers strategic value in advancing contemporary and future-oriented education.

From 2022 to 2024, research interest has increasingly shifted toward developing higher-order thinking skills, particularly critical thinking, as indicated by the growing prominence of related keywords. These findings further reinforce PBL's position as a highly effective method for cultivating critical thinking in mathematics education. Yu and Zin (2023) argue that the modern adaptation of PBL prioritizes the development of students' critical thinking abilities, and a growing body of evidence supports its positive outcomes in this regard. Through PBL, students are encouraged to memorize formulas and procedures and analyze and evaluate complex problems—essential skills in today's rapidly changing world (Thomassen & Stentoft, 2020).

Additionally, the presence of keywords such as secondary education, engineering, and mathematics underscores the significance of PBL in secondary-level instruction, particularly when mathematics is integrated with other disciplines. Implementing PBL at this level facilitates a more holistic and contextualized understanding of mathematics, aligning with industry demands and current global challenges (Tahiri, 2024). This shift reflects the increasingly complex dynamics of educational needs, pushing for more real-world and contextually relevant pedagogical approaches.

Several promising directions for future research in PBL for mathematics education have also emerged. These include the integration of artificial intelligence (AI) into the design of problem-based assignments, using learning analytics to track students' problem-solving processes in real-time, and transdisciplinary PBL approaches that connect mathematics with real-world social and environmental issues. Integrating AI in task design can support more personalized learning by adjusting the difficulty of problems to match students' abilities and needs (Kaledio et al., 2024). Meanwhile, learning analytics can provide educators with actionable insights into student progress, enabling timely and targeted feedback.

Transdisciplinary PBL, which combines mathematical learning with real-life challenges, particularly in social and environmental contexts, holds substantial potential for enhancing the relevance and impact of mathematics education. This approach enables students to apply mathematical concepts in solving complex, authentic problems across disciplines (Roberts et al., 2022). These emerging themes align closely with ongoing technological advancements and evolving educational demands, offering significant potential for developing adaptive, future-ready learning models.

6. Conclusion

This bibliometric study comprehensively analyzes publication patterns, emerging trends, and potential future research directions concerning implementing Problem-Based Learning (PBL) in school mathematics education from 2015 to 2024. The findings indicate that Indonesia and the United States are the leading countries in corresponding authorship, contributing the highest number of publications. Prominent Indonesian institutions—Universitas negeri Semarang, Universitas Pendidikan Indonesia, and Universitas Negeri Padang—stand out as the most active in publishing PBL-related research. At the author level, Capraro M.M., Arnawa I.M., and Capraro R.M. are identified as the most prolific contributors, while Han and Laforce are the most highly cited authors. Regarding publication venues, the Journal of Physics: Conference Series and AIP Conference Proceedings emerge as the most influential sources, reflecting their role in disseminating studies on PBL in mathematics education.

The thematic analysis of the literature reveals six core research themes. The most prominent theme involves the application of PBL to enhance students' critical thinking and problem-solving abilities, particularly through integrating educational technology. Additionally, PBL is widely embedded within project-based curricula that support STEM education and interdisciplinary learning. Its application spans multiple educational levels and is frequently supported by active learning and blended learning approaches, offering instructional flexibility. The development of mathematical thinking as an advanced cognitive skill also receives notable scholarly attention. Furthermore, the significant presence of Indonesian research contributions underscores the country's pivotal role in advancing the global discourse on PBL innovation in mathematics education.

Concerning future research directions, the study highlights increasing interest in integrating advanced technologies—such as artificial intelligence (AI) and learning analytics—within the PBL framework. Promising areas for further exploration include the design of AI-assisted problem-based assignments, using real-time learning analytics to monitor students' problem-solving processes, and the development of transdisciplinary PBL models that integrate mathematics with real-world social and environmental issues. These developments point toward a more adaptive, responsive, and personalized learning environment that better accommodates students' diverse needs. Moreover, the emergence of transdisciplinary approaches signals a broader research agenda aimed at fostering holistic education and equipping students to address complex global challenges.

While this study offers a comprehensive bibliometric analysis, certain limitations must be acknowledged. The analysis is based exclusively on metadata retrieved from the Scopus database, which may result in the omission of pertinent studies indexed in other scholarly repositories. Furthermore, the reliance on quantitative bibliometric indicators may limit the depth of contextual understanding, as it does not capture the qualitative dimensions that could enrich insights into the pedagogical development and implementation of PBL in mathematics education. Future research is therefore encouraged to adopt mixed-methods approaches that integrate bibliometric, content, and citation analyses to provide a more holistic view. Additionally, expanding the data sources to include other reputable academic databases, such as the Web of Science and ERIC, would enhance the breadth and representativeness of the findings. Researchers are also advised to investigate the practical application of technology-enhanced PBL in diverse educational contexts to assess its effectiveness, scalability, and pedagogical impact.

7. Suggestion

Based on recent developments in research on Problem-Based Learning (PBL) in mathematics education, future studies are encouraged to explore transdisciplinary approaches that integrate mathematics with real-world social and environmental issues. Additionally, incorporating artificial intelligence (AI) in problem-based tasks presents a promising direction for creating more personalized and adaptive learning experiences tailored to students' needs and abilities. Further investigation into learning analytics is also warranted, as it can provide real-time insights into students' problem-solving processes, enabling educators to deliver more targeted and timely feedback. Given the increasing focus on fostering higher-order thinking skills, particularly critical thinking, future research should also examine the effectiveness of PBL models integrated with STEM education and digital technologies in enhancing these competencies at the secondary education level. Such efforts will strengthen the relevance of mathematics education in addressing the increasingly complex and dynamic demands of the global landscape.

Declarations

Author Contributions. S.M.: Conceptualization, validation, writing - original draft preparation. S.T.: Formal analysis and investigation, supervision. A.T.: Writing - review and editing, data curation. H.I.: Methodology, resources.

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Data Availability Statement. The data used in this bibliometric analysis were obtained from publicly accessible academic databases, with Scopus selected as the primary source. This selection was based on the extensive and comprehensive coverage of peer-reviewed literature in relevant disciplines on the study of the use of PBL in school mathematics learning.

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