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Enhancing Students' Learning Outcomes in Chemistry through Problem-Based Learning: A Systematic Literature Review Supporting Sustainable Development Goal 4 (Quality Education)

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Abstract: This study aims to systematically analyze the effectiveness of Problem-Based Learning (PBL) in enhancing students' learning outcomes in chemistry education. This research employed a Systematic Literature Review (SLR) approach following PRISMA 2020 guidelines with strict inclusion criteria. A total of 30 empirical studies published between 2010 and 2025 were selected from Scopus- and SINTA-indexed journals. The findings indicate that PBL significantly improves students' conceptual understanding, critical thinking, and problem-solving skills, particularly in topics such as reaction rates, chemical equilibrium, and acid–base chemistry. Furthermore, the integration of PBL with digital media and contextual approaches strengthens its effectiveness in supporting meaningful learning. However, challenges related to teacher readiness and the need for appropriate scaffolding remain critical issues. This study contributes to the achievement of Sustainable Development Goal 4 (Quality Education) by promoting effective student-centered learning strategies in chemistry education.

Keywords: Bibliometric analysis; Chemistry education; Critical thinking; Learning outcomes; Problem-based learning

Introduction

Chemistry learning is a branch of science characterized by its complexity, as it involves the simultaneous integration of macroscopic, microscopic, and symbolic representations. This complexity often becomes a major obstacle for students in developing a comprehensive and in-depth understanding of chemical concepts. According to Johnstone (1991), difficulties in learning chemistry arise from the high cognitive demands required to integrate these multiple representations. Furthermore, several studies have shown that students frequently experience misconceptions due to insufficient conceptual understanding (Taber, 2013; Nakhleh, 1992). The high cognitive load inherent in chemistry learning contributes significantly to students' low academic achievement (Milenkovic et al., 2014).

In practice, chemistry instruction in schools is still largely dominated by conventional teacher-centered approaches, where students tend to be passive recipients of information. Such approaches are considered less effective in fostering higher-order thinking skills, which are essential in 21st-century education. Prince (2004) argues that active learning has a significantly greater impact on conceptual understanding compared to passive instruction. This is consistent with the constructivist perspective, which posits that knowledge is actively constructed by learners through meaningful learning experiences (Bodner, 1986).

In the context of modern education, students are expected to possess critical thinking, creativity, and problem-solving skills. Therefore, it is necessary to

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implement instructional models that can accommodate these competencies. One of the most relevant approaches is Problem-Based Learning (PBL), which uses real-world problems as the context for learning. PBL enables students to develop critical thinking and problem-solving skills through active engagement in the learning process (Hmelo-Silver, 2004; Savery, 2006).

Problem-Based Learning was originally developed in medical education and has since been adapted to various disciplines, including chemistry (Barrows & Tamblyn, 1980; Schmidt, 1993). In its implementation, PBL emphasizes student-centered learning, where the teacher acts as a facilitator. The learning process begins with the presentation of authentic problems that students must solve through group discussions, information gathering, and data analysis (Dolmans et al., 2005). This model also promotes collaboration and communication among students, making learning more interactive and meaningful (Hmelo-Silver et al., 2007; Annam et al., 2023; Doyan et al., 2024). In chemistry education, PBL is particularly relevant because it helps bridge abstract concepts with real-life contexts.

Gilbert et al. (2009) emphasize the importance of multiple representations in enhancing students' understanding of chemistry concepts. PBL provides opportunities for students to explore these representations in an integrated manner. Moreover, PBL supports the development of problem-solving skills, which are central to chemistry learning (Jonassen, 2011; Cooper, 2010). Numerous empirical studies have demonstrated the positive impact of PBL on students' learning outcomes in chemistry. Dini et al. (2023) found that the implementation of PBL significantly improved students' learning activities and achievement. Similarly, Juliana (2022) reported that PBL effectively enhanced students' understanding of electron configuration concepts. In addition, Fareza et al. (2024) revealed that PBL significantly improved students' chemical literacy and critical thinking skills in reaction rate topics.

Further studies indicate that PBL can be integrated with various instructional media to enhance its effectiveness. Martiana et al. (2025) developed PBL-based chemistry modules that successfully improved students' numeracy literacy. Meanwhile, Virginia (2025) demonstrated that PBL-based worksheets on green chemistry topics enhanced students' critical thinking skills. These findings highlight the flexibility of PBL in accommodating various instructional innovations.

Moreover, a systematic review conducted by Raman et al. (2024) concluded that PBL consistently improves students' problem-solving abilities in chemistry education. Varadarajan et al. (2024) also reported that PBL is effective in laboratory-based chemistry learning, enhancing both practical skills and conceptual understanding. In the Indonesian context, Shiddiqi et al. (2025) identified a growing trend in the use of PBL in chemistry education, with consistently positive outcomes.

Despite its advantages, the implementation of PBL is not without challenges. Hung (2011) identified that one of the main challenges is the readiness of both teachers and students to adapt to this student-centered approach. Additionally, Mayer (2004) and Kirschner et al. (2006) argued that minimal guidance during instruction may lead to student confusion if not properly designed. Therefore, appropriate scaffolding strategies are essential to ensure the effectiveness of PBL (Hmelo-Silver et al., 2007).

Beyond cognitive outcomes, PBL also contributes to the development of students' social and affective skills. It encourages collaboration, communication, and respect for diverse perspectives. This aligns with the broader goals of education, which aim to develop not only academically competent individuals but also socially responsible citizens (Eilks, 2015).

However, findings regarding the effectiveness of PBL remain varied and are influenced by several factors, including learning materials, student characteristics, and implementation strategies (Annam et al., 2024). Therefore, a more comprehensive analysis is needed to synthesize these diverse findings. A hybrid review approach, which combines systematic and narrative review methods, is considered suitable for providing a holistic understanding of PBL effectiveness in chemistry learning.

The hybrid review approach allows researchers to systematically analyze existing studies while also offering in-depth interpretations of their findings. Through this approach, it is expected that a more comprehensive understanding of the strengths, limitations, and influencing factors of PBL can be achieved. In conclusion, Problem-Based Learning is a promising instructional model for improving students' learning outcomes in chemistry. It not only enhances conceptual understanding but also fosters critical thinking, problem-solving, and social skills. However, to obtain a more comprehensive understanding of its effectiveness, further investigation through a hybrid review approach is necessary.

Therefore, this study aims to analyze and describe research trend on the effectiveness of Problem-Based Learning in improving students' learning outcomes in chemistry through a hybrid review approach, thereby contributing to the development of more effective and innovative chemistry teaching practices.

This study contributes to addressing these challenges by providing a comprehensive synthesis of empirical findings on the effectiveness of PBL in chemistry education. Furthermore, this research is aligned with Sustainable Development Goal 4 (Quality

Education), which emphasizes inclusive and equitable education. By promoting student-centered learning approaches such as Problem-Based Learning, this study supports the development of critical thinking, problem-solving skills, and meaningful learning experiences necessary for 21st-century education.

Method

Research Design

This study employed a hybrid review approach, integrating a Systematic Literature Review (SLR) with bibliometric analysis to comprehensively examine the effectiveness of Problem-Based Learning (PBL) in improving students' learning outcomes in chemistry education. The hybrid review approach enables both in-depth qualitative synthesis and quantitative mapping of research trends, thereby providing a holistic understanding of the topic (Paul & Criado, 2020; Donthu et al., 2021).

The SLR component followed structured and transparent procedures to identify, evaluate, and synthesize relevant studies, while the bibliometric analysis was used to analyze publication trends, research productivity, and thematic development within the field. This combination ensures both rigor and breadth in analyzing the existing literature (Snyder, 2019).

Data Sources and Research Strategy

The systematic review process in this study adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure transparency, reproducibility, and methodological rigor (Page et al., 2021). Search strategy used multiple databases, but included studies were from Scopus and SINTA journals only.

The search was performed using combinations of the following keywords: "Problem-Based Learning" OR "PBL", "Chemistry Education", "Learning Outcomes", "Critical Thinking", "Chemical Literacy". Boolean operators (AND, OR) were used to refine the search and ensure relevant results (Gusenbauer & Haddaway, 2020).

Inclusion and Exclusion Criteria

To ensure relevance, quality, and transparency, explicit inclusion and exclusion criteria were applied following established SLR guidelines (Petticrew & Roberts, 2006; Page et al., 2021).

Table 1. Inclusion and Exclusion Criteria of SLR

Inclusion criteria	Exclusion criteria
Articles published between 2010–2025	Non-English and non-Indonesian articles
Peer-reviewed journal articles	Conference papers, theses, or dissertations
Studies focusing on PBL in chemistry education	Studies not directly related to chemistry learning
Studies reporting learning outcomes (cognitive, affective, or skills)	Articles without empirical or review data
Indexed in Scopus or SINTA	

Systematic Literature Review Procedure

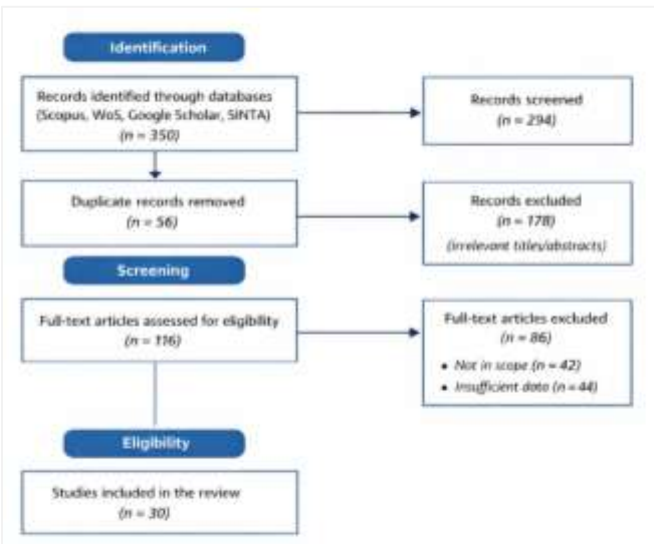

Figure 1. PRISMA flow diagram of study selection

The SLR procedure adhered strictly to the PRISMA 2020 guidelines to ensure methodological rigor and replicability (Page et al., 2021). The review process involved four stages: identification, screening, eligibility, and inclusion.

Data from selected studies were extracted systematically using a structured matrix, including Author(s) and year, Research design, Sample characteristics, Chemistry topic, Type of PBL implementation and Key findings. The extracted data were analyzed using a thematic synthesis approach to identify patterns, similarities, and differences across studies (Thomas & Harden, 2008).

Bibliometric Review Procedure

Bibliometric analysis was conducted to complement the SLR by quantitatively mapping research trends in PBL within chemistry education. The data were obtained primarily from the Scopus database, which is widely recognized for its comprehensive coverage of high-quality publications (Donthu et al., 2021). The analysis was performed using the VOSviewer for network visualization (co-authorship, co-occurrence, citation analysis) (van Eck & Waltman, 2010).

The bibliometric analysis focused on several key indicators: Publication Trends (annual growth of publications), global distribution by country, Most Productive Authors and Institutions, Source Analysis (journals contributing to the field), Keyword Co-occurrence Analysis (research themes) and Citation Analysis (impact and influential studies). These indicators provide insights into the development, structure, and dynamics of research on PBL in chemistry education (Donthu et al., 2021). Network visualization techniques were used to identify relationships among Authors (co-authorship networks), Keywords (research trends and clusters) and Articles (citation and co-citation patterns). This approach helps reveal dominant themes and emerging research directions in the field (van Eck & Waltman, 2010).

The final stage involved integrating findings from both SLR and bibliometric analysis. The synthesis focused on Effectiveness of PBL in improving learning outcomes, Trends and research gaps and Factors influencing PBL implementation. This integrative approach allows for a deeper and more comprehensive understanding of the research topic (Paul & Criado, 2020).

This systematic approach ensures transparency, rigor, and reproducibility, while also supporting evidence-based educational practices aligned with Sustainable Development Goal 4 (Quality Education).

Result and Discussion

All figures, tables, and visualizations presented in this study were generated using original data analysis and software tools (e.g., VOSviewer) to ensure clarity and avoid the use of scanned images. High-resolution images were used to enhance readability and data interpretation. Supporting literature was also incorporated in each analysis to strengthen the validity of the research findings. Additionally, documentation of the research process, including data screening and analysis stages, is presented to provide transparency and strengthen methodological rigor.

This research aims to analyze and describe research trend on the effectiveness of Problem-Based Learning in improving students' learning outcomes in chemistry. Figure 2 below is presented regarding research trends on the effectiveness of Problem-Based Learning in improving students' learning outcomes in chemistry in the las ten years.

Figure 2 shows that the trend in research on the effectiveness of Problem-Based Learning in improving students' learning outcomes in chemistry experiencing increases and decreases.

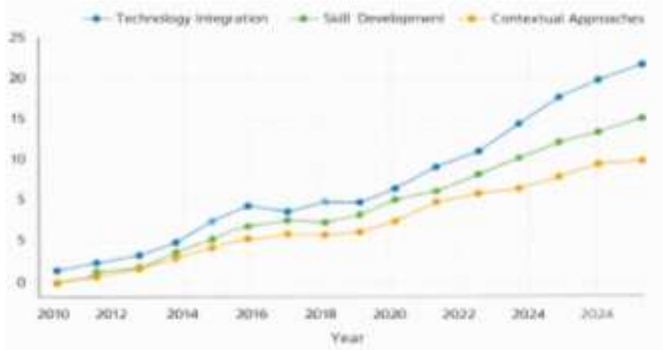

Figure 2. Research trends on PBL in chemistry education (2010-2025)

The trend analysis presented in Figure 2 illustrates the development of research on Problem-Based Learning (PBL) in chemistry education over the period 2010–2025, with a focus on three main dimensions: technology integration, skill development, and contextual approaches. The figure shows a consistent upward trend in the number of publications across all three dimensions. This indicates a growing interest among researchers in exploring innovative and student-centered learning approaches in chemistry education. The increase becomes particularly significant after 2018, suggesting a shift toward more modern pedagogical frameworks aligned with 21st-century learning demands (Donthu et al., 2021).

The technology integration dimension demonstrates the most significant growth compared to the other variables. Starting from a relatively low number of publications in 2010, this trend increases sharply, especially after 2020, reaching its peak in 2025. This pattern reflects the rapid advancement of digital technologies and their integration into educational practices. The increasing use of e-learning platforms, virtual laboratories, and digital simulations has enhanced the implementation of PBL in chemistry education. These findings are consistent with recent studies emphasizing the role of digital tools in improving student engagement and learning outcomes (Martiana et al., 2025; Virginia, 2025).

The skill development trend also shows steady growth throughout the observed period. This dimension includes research focusing on critical thinking, problem-solving, and higher-order cognitive skills. The continuous increase in this area highlights the strong emphasis on developing students' competencies beyond mere content knowledge. This aligns with the fundamental objective of PBL, which is to foster higher-order thinking skills (Zoller, 2002). Moreover, the trend supports findings from previous studies indicating that

PBL significantly enhances students' cognitive and metacognitive abilities (Jonassen, 2011; Fareza et al., 2024).

The contextual approaches dimension shows moderate but consistent growth. This category includes studies that integrate real-world contexts, such as environmental issues, green chemistry, and culturally responsive teaching, into PBL. Although the growth is not as steep as in technology integration, the increasing number of publications suggests a growing recognition of the importance of contextualizing chemistry learning. Contextual approaches help students connect abstract concepts with real-life applications, thereby enhancing meaningful learning (Gilbert & Treagust, 2009).

When comparing the three dimensions, it is evident that Technology integration is the most rapidly growing research area, indicating a strong shift toward digital and hybrid learning environments. Skill development remains a core focus, reflecting the essential role of PBL in fostering higher-order thinking. Contextual approaches serve as a complementary dimension, supporting the relevance and applicability of chemistry learning. The convergence of these three dimensions suggests that future research will likely focus on integrated approaches, combining digital tools, skill development, and real-world contexts within PBL frameworks.

The observed trends provide several important implications which are the increasing dominance of technology integration suggests the need for further exploration of digital PBL models, including AI-supported and virtual learning environments. The steady growth in skill development highlights the importance of designing assessments that measure higher-order thinking skills. And the rise of contextual approaches indicates a need for more research on sustainability and interdisciplinary learning in chemistry education.

Below are also figure 3 presented the global distribution of research on Problem-Based Learning (PBL) in chemistry education across different countries during the period 2010–2025. The visualization uses a choropleth map to illustrate the number of publications, with darker shades indicating higher research productivity.

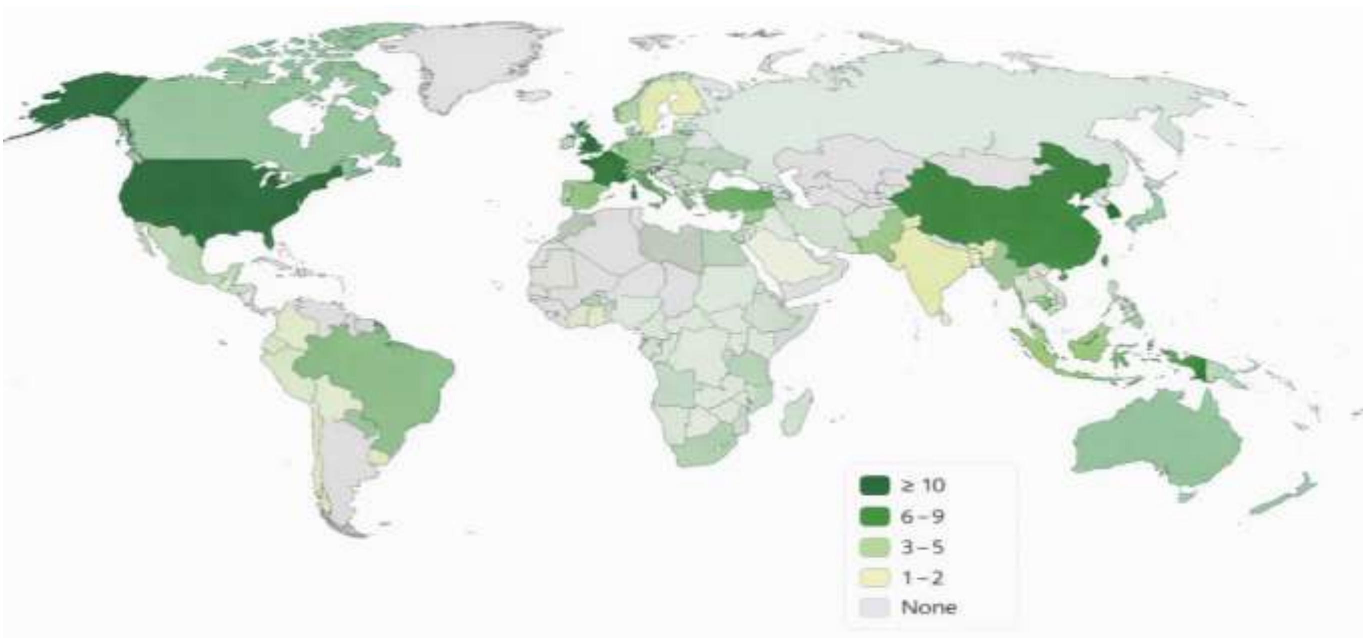

Figure 3. Global distribution of PBL research in chemistry education by country (2010-2025)

Figure 3 reveals that PBL research in chemistry education is globally distributed but unevenly concentrated, with significant contributions coming from specific regions. The highest research productivity is observed in countries with well-established education research systems and strong academic publication cultures. The map indicates that countries such as the United States, China, and the United Kingdom are among the most productive contributors to PBL research in chemistry education. These countries are represented by darker color intensities, reflecting a higher number of publications. This dominance can be attributed to several factors, including Strong investment in educational research, advanced higher education systems and Greater access to international publication platforms. These findings are consistent with global bibliometric trends showing that developed countries tend to dominate scientific research output (Donthu et al., 2021).

In addition to leading countries, several emerging contributors are visible, particularly in Asia and Southeast Asia, including Indonesia, Malaysia, and India. Although the number of publications in these countries is lower compared to leading nations, the increasing color intensity suggests a growing research interest and productivity. In the context of Indonesia, the increasing number of publications is aligned with the rising adoption of innovative learning models such as PBL in chemistry education, as highlighted by Shiddiqi et al. (2025). This trend reflects ongoing efforts to improve the quality of education and research at the national level.

The visualization also highlights several regional patterns which are North America and Europe: High research productivity and strong collaboration networks, Asia: Rapid growth in research output, particularly in China, India, and Southeast Asia and Africa and South America: Limited but gradually increasing contributions. These patterns indicate disparities in research capacity and access to academic resources across regions. The uneven distribution of research output suggests opportunities for international collaboration. Countries with lower research productivity could benefit from partnerships with leading research institutions to enhance knowledge exchange and capacity building. Collaboration networks, as indicated in bibliometric studies, play a crucial role in increasing research impact and visibility (Donthu et al., 2021).

Results of Systematic Literature Review (SLR)

Based on the PRISMA selection process, a total of 30 articles were included in the final analysis, consisting of empirical studies (quantitative, quasi-experimental, and mixed methods) and review articles. These studies were published between 2010 and 2025, with a noticeable increase in publications after 2018, indicating growing interest in Problem-Based Learning (PBL) in chemistry education. The distribution of studies shows that most research was conducted at the secondary school level, particularly in topics such as reaction rates, chemical equilibrium, hydrocarbons, and acid-base chemistry. Several studies also focused on laboratory-based learning and the integration of digital media.

Effectiveness of PBL on Learning Outcomes

The synthesis of the selected studies indicates that PBL has a consistently positive impact on students' learning outcomes in chemistry. Several empirical studies reported significant improvements in cognitive achievement. For example, Dini et al. (2023) found that students taught using PBL showed higher post-test scores compared to those taught using conventional methods. Similarly, Juliana (2022) demonstrated that PBL improved students' understanding of electron configuration concepts. In addition, Fareza et al. (2024) reported that PBL significantly enhanced students' chemical literacy and critical thinking skills, particularly in reaction rate topics. These findings are supported by Raman et al. (2024), who concluded through a systematic review that PBL effectively improves problem-solving abilities in chemistry education. Furthermore, In addition, problem-based learning has been reported to significantly increase student engagement in science learning by actively involving learners in collaborative problem-solving activities (Wibowo & Santoso, 2022). This increased engagement contributes to deeper understanding and sustained learning motivation in chemistry classrooms.

Recent studies further strengthen the evidence that Problem-Based Learning (PBL) plays a crucial role in enhancing multidimensional learning outcomes in chemistry education. Empirical and review-based findings indicate that PBL not only improves students' academic performance but also significantly enhances engagement, motivation, and critical thinking skills (Arsyad et al., 2024; Rusmansyah et al., 2025). The integration of PBL with contextual approaches such as socio-scientific issues has been shown to effectively develop students' chemical literacy and real-world problem-solving abilities (Putri et al., 2025). In addition, hybrid models combining PBL with frameworks such as STEM and SETS further strengthen students' analytical and reasoning skills in addressing complex chemical problems (Mulyani et al., 2025). The development of PBL-based instructional materials, including modules and digital learning resources, also contributes to improving numeracy literacy and conceptual understanding (Martiana et al., 2025). From a broader perspective, systematic reviews and bibliometric studies reveal that PBL research continues to grow rapidly and demonstrates consistent effectiveness across diverse educational contexts (Shiddiqi et al., 2025; Varadarajan, 2024). Furthermore, recent meta-analyses highlight that problem-based and inquiry-oriented approaches significantly foster creativity and higher-order thinking skills in science education (Pinar et al., 2025). Similar trends are observed in project-based learning studies, which share conceptual similarities with PBL and show strong impacts on conceptual understanding and collaboration skills (Islawati et al., 2025). Overall, these findings confirm that PBL is not only pedagogically effective but also highly adaptable to modern educational demands, particularly when integrated with technology and interdisciplinary approaches.

Integration with Instructional Media

Another important finding is that the effectiveness of PBL is further enhanced when integrated with instructional media. Martiana et al. (2025) developed PBL-based modules that improved students' numeracy literacy, while Virginia (2025) demonstrated that PBL worksheets on green chemistry significantly improved critical thinking skills. This suggests that PBL is highly adaptable and can be combined with various instructional innovations, including digital learning tools and contextual teaching approaches.

Below are the bibliometric visualization generated using VOSviewer provides a comprehensive overview of the research landscape on Problem-Based Learning (PBL) in chemistry education. The network maps illustrate the relationships among keywords, research themes, and citation patterns, revealing the intellectual structure and development of the field.

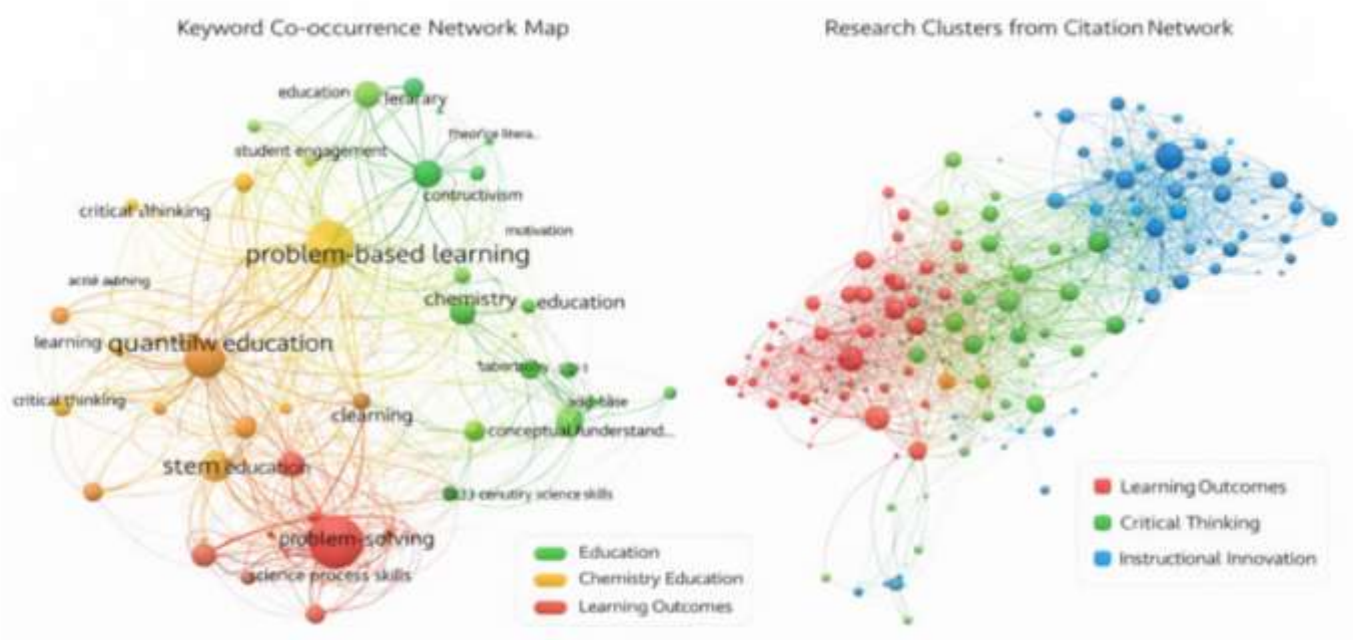

Figure 4. VOSviewer network maps of keyword co-occurrence (left) and citation network clustering (right) in PBL research on chemistry education

The keyword co-occurrence map shows that "problem-based learning" appears as the central node with the highest frequency and strongest link strength, indicating its dominant role in the research domain. This centrality suggests that PBL serves as the primary conceptual framework connecting various research topics in chemistry education. Several clusters are identified in the visualization: Cluster 1 (Red): Learning Outcomes and Academic Achievement, This cluster includes keywords such as learning outcomes, achievement, and student performance. The prominence of this cluster indicates that a significant portion of research focuses on measuring the effectiveness of PBL in improving students' academic performance. This finding aligns with previous studies demonstrating that PBL positively influences cognitive learning outcomes (Dini et al., 2023; Juliana, 2022). Cluster 2 (Green): Critical Thinking and Problem-Solving Skills, Keywords such as critical thinking, problem-solving, and higher-order thinking skills dominate this cluster. This reflects the strong emphasis on developing students' cognitive skills through PBL. The findings support the argument that PBL fosters higher-order thinking, as highlighted by Zoller (2002) and Jonassen (2011). Cluster 3 (Blue): Instructional Innovation and Digital Learning, This cluster includes keywords such as e-learning, digital media, and instructional design. The presence of this cluster indicates an emerging trend in integrating PBL with technology-enhanced learning environments. This is consistent with recent studies that combine PBL with digital tools to improve learning effectiveness (Martiana et al., 2025; Virginia, 2025). The proximity between clusters suggests strong interconnections among these research themes, indicating that learning outcomes, critical thinking, and instructional innovation are closely related dimensions in PBL research.

The citation network visualization highlights influential studies and their relationships within the research field. Highly cited works, such as those by Hmelo-Silver (2004), Savery (2006), and Schmidt (1993), appear as central nodes, indicating their foundational role in the development of PBL theory. The co-citation analysis reveals that studies on constructivist learning theory, scaffolding, and problem-solving are frequently cited together. This suggests that the theoretical foundation of PBL research is strongly rooted in constructivist principles (Bodner, 1986) and supported by scaffolding strategies to enhance learning effectiveness (Hmelo-Silver et al., 2007).

The bibliometric findings complement the SLR results by providing quantitative evidence of research trends and thematic structures. While the SLR highlights the effectiveness of PBL based on empirical studies, the bibliometric analysis reveals how the research field has evolved and identifies emerging areas of interest. The integration of these two approaches strengthens the validity of the study and provides a more comprehensive understanding of the effectiveness of PBL in chemistry education (Snyder, 2019; Donthu et al., 2021).

PBL and Constructivist Learning Theory

The effectiveness of PBL can be explained through the lens of constructivist learning theory. According to Bodner (1986), knowledge is actively constructed by learners rather than passively received. PBL aligns with this principle by engaging students in problem-solving activities that require active participation and knowledge construction.

Moreover, PBL facilitates meaningful learning by connecting abstract chemical concepts with real-life contexts (Gilbert & Treagust, 2009). This is particularly important in chemistry, where students often struggle to relate theoretical concepts to practical applications.

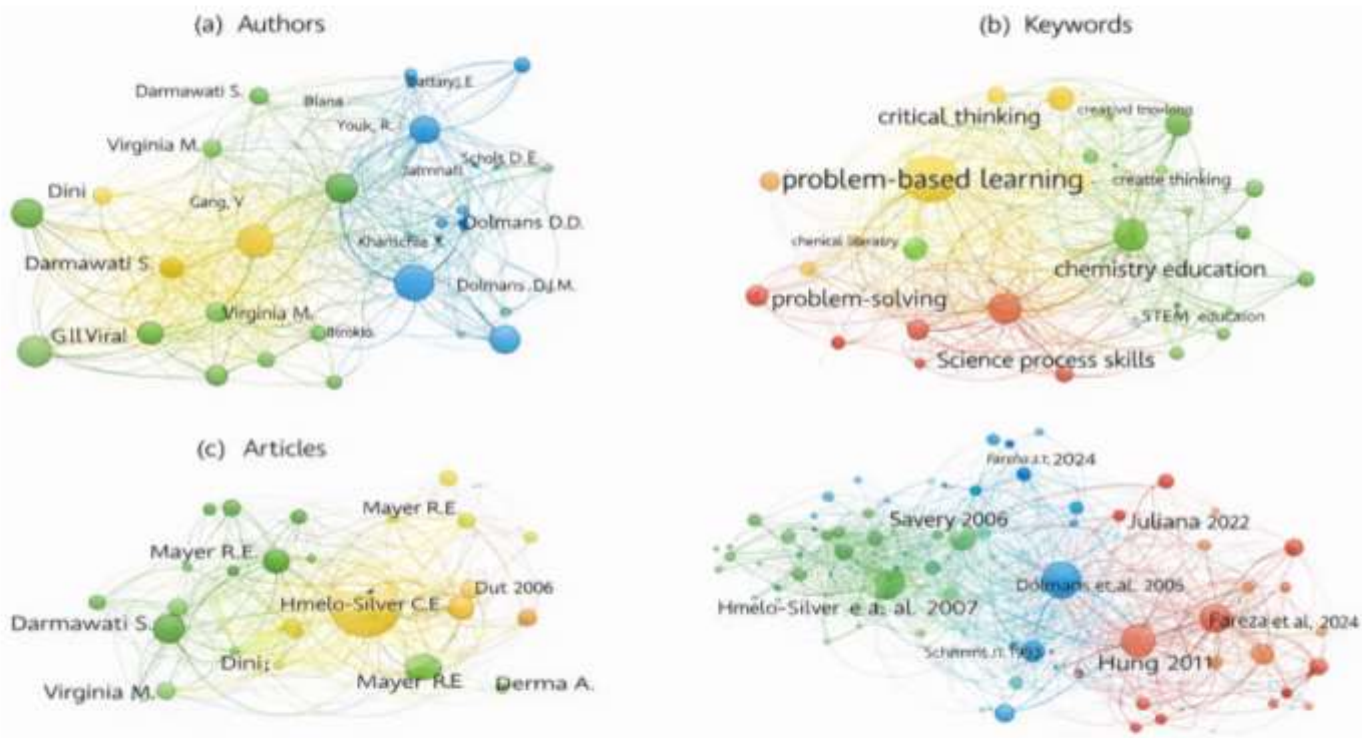

Figure 5. VOSviewer network visualization of authors (co-authorship networks). Keywords (research trends and clusters), and articles (citation and co-citation patterns) in PBL research in chemistry education

Figure 5 above presents a comprehensive network visualization of co-authorship (authors), keyword co-occurrence (research trends), and citation/co-citation patterns (articles) in the field of Problem-Based Learning (PBL) in chemistry education. These visualizations provide deeper insights into the intellectual structure, collaboration patterns, and thematic development of the research domain.

Co-authorship Network (Authors)

The co-authorship network illustrates the collaborative relationships among researchers in the field. Each node represents an author, while the links indicate co-authorship connections. The size of the nodes reflects the number of publications, and the clustering indicates research groups or collaboration networks. The visualization reveals several distinct clusters, indicating that research on PBL in chemistry education is conducted within collaborative groups rather than isolated individuals. Some authors appear as central nodes with strong link strengths, suggesting that they play key roles in connecting different research groups. This pattern highlights the importance of academic collaboration in advancing PBL research.

Strong collaboration networks are often associated with higher research productivity and impact, as knowledge and expertise are shared across institutions and countries (Donthu et al., 2021). However, the presence of multiple clusters with limited interconnections also suggests that collaboration across research groups is still somewhat fragmented. This indicates opportunities for strengthening international and interdisciplinary collaboration in future research.

Keyword Co-occurrence Network (Research Trends and Clusters)

The keyword co-occurrence network provides insights into the main research themes and their relationships. The visualization shows that "problem-based learning" is the most dominant and central keyword, confirming its role as the core focus of the research field. Several major clusters included Cluster 1: Learning Outcomes and Problem-Solving Includes keywords such as learning outcomes, problem-solving, and science process skills. This cluster emphasizes the effectiveness of PBL in improving students' academic performance and cognitive abilities. Cluster 2: Critical Thinking and Higher-Order Skills Includes critical thinking, creative thinking, and higher-order thinking skills. This reflects the strong focus on developing students' cognitive competencies through PBL, consistent with the framework of higher-order cognitive skills (Zoller, 2002). Cluster 3: Chemistry Education and Instructional Context Includes chemistry education, STEM education, and chemical literacy. This cluster highlights the application of PBL within specific disciplinary and contextual frameworks. The proximity and interconnections among these clusters indicate that research themes are highly interrelated, suggesting that PBL simultaneously addresses multiple dimensions of learning.

Citation and Co-citation Network (Articles)

The citation and co-citation network identifies the most influential studies and their relationships. Nodes represent individual articles, while links indicate citation relationships. Larger nodes represent highly cited works, reflecting their influence in shaping the research field. The visualization reveals that foundational works, such as those by Hmelo-Silver (2004), Savery (2006), and Schmidt (1993), occupy central positions in the network. These studies form the theoretical backbone of PBL research. Additionally, more recent studies, such as Fareza et al. (2024) and Juliana (2022), are connected to these foundational works, indicating the continuity and evolution of research. This pattern suggests that current studies build upon established theories while extending them into new contexts, such as chemistry education and digital learning environments. The clustering of articles also reflects thematic groupings, including Theoretical foundations of PBL, Empirical studies on learning outcomes and Innovations in instructional design.

The network visualization findings are consistent with the VOSviewer cluster analysis, research trend graph, and global distribution map presented earlier. While previous analyses highlighted trends and geographical distribution, this network analysis provides deeper insights into the structural relationships within the research field. This triangulation strengthens the validity of the study and confirms that PBL research in chemistry education is a dynamic and evolving field with strong theoretical and empirical foundations (Snyder, 2019; Donthu et al., 2021).

Enhancement of Higher-Order Thinking Skills

One of the key strengths of PBL is its ability to promote higher-order thinking skills. As noted by Zoller (2002), chemistry education should emphasize higher-order cognitive skills (HOCS) rather than lower-order skills. The findings of this study confirm that PBL effectively develops critical thinking, problem-solving, and analytical skills. This is consistent with Jonassen (2011), who emphasized that problem-solving is a central component of meaningful learning. Through PBL, students are encouraged to analyze problems, evaluate information, and propose solutions, thereby enhancing their cognitive abilities.

Challenges in Implementation

Despite its effectiveness, several challenges in implementing PBL were identified. Hung (2011) highlighted that both teachers and students may face difficulties in adapting to this student-centered approach. Additionally, Kirschner et al. (2006) and Mayer (2004) argued that insufficient instructional guidance may hinder learning outcomes. Therefore, appropriate scaffolding is essential to ensure that students can effectively engage in problem-solving activities (Hmelo-Silver et al., 2007). Teachers play a crucial role in facilitating discussions, guiding inquiry, and providing feedback.

These findings have important implications for achieving Sustainable Development Goal 4 (Quality Education). The effectiveness of Problem-Based Learning in improving students' conceptual understanding, critical thinking, and problem-solving skills indicates that this model supports high-quality and student-centered education. Furthermore, the integration of digital tools within PBL enhances accessibility and inclusivity, which are essential components of modern education systems.

Conclusion

This study concludes that Problem-Based Learning (PBL) is an effective instructional model for enhancing students' learning outcomes in chemistry, particularly in improving conceptual understanding, critical thinking, and problem-solving skills. The integration of PBL with digital and contextual approaches further strengthens its effectiveness. However, successful implementation depends on teacher readiness and appropriate scaffolding strategies. Importantly, this study contributes to the achievement of Sustainable Development Goal 4 (Quality Education) by highlighting the role of student-centered learning in improving educational quality. Future research is recommended to explore technology-integrated PBL models and expand implementation across diverse educational contexts.

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Conceptualization, E.L. and F.; methodology, E.L., F., and Y.; formal analysis, E.L.; investigation, E.L.; resources, F., Y., Yk., and S.D.; writing—original draft preparation, E.L.; writing—review and editing, F., Y., Yk., and S.D.; visualization, E.L.; supervision, F. and Y.; project administration, E.L.; funding acquisition, F. and Y. All authors have read and approved the published version of the manuscript.

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