THE INTERDISCIPLINARY JOURNAL OF PROBLEM-BASED LEARNING

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IJPBL is Published in Open Access Format through the Generous Support of the College of Information at University of North Texas, the College of Education and Human Development at University of North Dakota, and the Friday Institute for Educational Innovation at North Carolina State University.

https://doi.org/10.14434/ijpbl.v20i1.37007 Spring 2026 | Volume 20 | Issue 1

The Interdisciplinary Journal of Problem-based Learning

2026 Spring Issue

Unveiling the Global Instructional Impact of Problem-Based Learning in Science Education: A Comprehensive Systematic Review

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ABSTRACT

This study aimed to explore the application of problem-based learning (PBL) in science education in different countries. PBL is considered an effective learning approach for developing critical thinking, collaboration, and problem-solving skills; however, its implementation is often hampered by challenges in instructional design, limited resources, and diverse social and cultural contexts. Therefore, the current findings related to the application of PBL in science education were examined through a systematic literature review approach. The method used is a comprehensive analysis of various studies that discuss the effectiveness of PBL in various countries. The results suggest that although PBL enhances students' critical thinking and collaboration skills, its success is strongly influenced by adaptive instructional design, adaptation of learning materials to the local context, and teacher training. Furthermore, cultural and social diversity also influences how students interact with learning. The findings suggest the importance of developing a more adaptive and context-based curriculum, integrating technology, and customizing project-based evaluation to support students' active engagement in the learning process. The results guide future curriculum innovation in science education.

Keywords: *global impact, comparative study, problem-based learning (PBL), learning outcomes, curriculum development*

Problem-based learning (PBL) is a pedagogical approach first developed by the McMaster School of Medicine in Canada in 1965 (Tan, 2003; Walton & Matthews, 1989). The development has been driven by the need to address limitations in traditional lecture-based education, particularly in preparing medical students to tackle real-world problems (Perusso & Leal, 2022). The approach emphasizes creating a learning environment in which students develop critical thinking, problem-solving, and self-directed learning skills (Lonergan et al., 2022). The need has arisen from the recognition that passive learning methods are insufficient for equipping students with the competencies required in dynamic and interdisciplinary professional settings (Nantha et al., 2022). Dr. Howard Barrows later refined PBL in 1988 as both a process-oriented and curriculum-integrated strategy (Barrows, 1996). At its core, PBL is a student-centered approach that emphasizes active learning through the resolution of ill-defined problems, requiring the application of prior knowledge while acquiring new knowledge (Barrows, 1996; Ram, 1999). The method typically involves collaborative learning in which students work in groups to define problems, develop hypotheses, research solutions, and reflect on their findings (Marthaliakirana et al., 2022).

PBL has been implemented in various ways across disciplines and educational contexts (Aslan, 2021). One of the most widely adopted variations is the seven-step procedure, which includes (a) clarifying unfamiliar terms and concepts, (b) defining the problem, (c) analyzing the problem, (d) structuring and prioritizing the issues, (e) formulating learning objectives, (f) self-directed learning, and (g) synthesizing and applying the acquired knowledge (Lonergan et al., 2022). In science education, this procedure supports students in systematically investigating scientific phenomena and developing hypotheses, which are essential for understanding complex, interdisciplinary problems (Siew et al., 2015). By following these structured steps, learners can apply theoretical knowledge to practical scenarios, thereby deepening their understanding of scientific concepts and processes (Akhdinirwanto et al., 2020). The approach fosters cognitive and social development by providing students with control over their learning processes and encouraging collaboration (Su, 2022).

Several studies have highlighted the effectiveness of PBL in enhancing specific skills. For instance, PBL is associated with improvements in scientific creativity (Gholami et al., 2016), critical thinking (Akhdinirwanto et al., 2020), and communication skills (Aslan, 2021; Lonergan et al., 2022). Furthermore, studies by Tosun and Yasar (2013) and Kong et al. (2014) have demonstrated that PBL has not only enhanced these cognitive and interpersonal skills but also fostered deeper conceptual understanding and student motivation across diverse disciplines and educational levels globally. However, the implementation of PBL has also faced criticism. While some researchers have argued that PBL does not significantly outperform traditional, teacher-centered instructional methods, such as lectures and direct instruction in developing problem-solving skills (Page et al., 2021; Sharma et al., 2023), others have demonstrated its superior effectiveness in enhancing students' problem-solving abilities and conceptual understanding, particularly among junior high school and undergraduate students (Nantha et al., 2022; Su, 2022). In contrast, several studies have reported mixed or negative effects, including research by Schmidt et al. (2009) who contend that problem-solving skills cannot be directly taught through PBL and that the method's primary benefit lies in facilitating knowledge acquisition rather than problem-solving development.

Despite its potential, PBL's global application is not without challenges. For instance, cultural differences shape how students and teachers engage with PBL (Frambach, Driessen, & van der Vleuten, 2014); in some collectivist cultures, students may be less accustomed to the independent learning and critical questioning encouraged by PBL (Hung et al., 2019; Strobel & van Barneveld, 2009). Educational policies, such as rigid curricula or high-stakes testing, limit the flexibility needed for effective PBL implementation (Frambach, Driessen, Beh, et al., 2014). Resource availability also plays a significant role, as schools in under-resourced areas often lack access to trained facilitators or necessary materials. Additionally, varying teacher competencies, particularly in facilitating open-ended inquiry, significantly impact the success of PBL in fostering critical thinking and problem-solving skills (Strobel & van Barneveld, 2009).

The issues have underscored the need for a systematic exploration of PBL's adaptation and impact across diverse educational settings. Moreover, while meta-analyses and reviews have examined PBL's effectiveness in specific contexts, such as assessment models (e.g., Dochy et al., 2003; Gao et al., 2022; Liu & Pásztor, 2022; Sharma et al., 2023), there has been a lack of comprehensive, cross-border analyses focusing on its application in science education. With the global emphasis on enhancing 21st-century skills through innovative teaching models, the systematic examination of PBL in science education becomes increasingly critical. A global perspective enables the identification of best practices and contextual challenges, offering valuable insights for future adaptations. By integrating findings from diverse cultural and educational contexts, this review provides a comprehensive understanding of how PBL can be optimized to foster critical thinking, creativity, and problem solving in science learning environments. The insights gained from this review have informed the development of professional training programs for educators, guided the adaptation of PBL frameworks to diverse classroom settings, and supported the creation of resource materials tailored to specific cultural and educational needs. However, to synthesize existing research, this review examines key variables particularly students' problem-solving skills, conceptual understanding, and learning engagement, as well as how these outcomes are shaped by cultural factors, educational policies, and the characteristics of learning environments. By building on foundational studies (Hung et al., 2019; Loyens et al., 2023; Strobel & van Barneveld, 2009), it aimed to establish a robust theoretical framework and identify practical implications for educators and policymakers. Ultimately, the research contributes to the global discourse on PBL and its potential to transform science education.

Research Questions

The review focused on science education due to its critical role in developing 21st-century skills such as critical thinking, creativity, and problem solving, which are essential for addressing global challenges. Empirical evidence highlighted the unique opportunities and challenges posed by PBL in science contexts, including the need for interdisciplinary learning and the application of theoretical knowledge to real-world problems. To address the identified gaps in the literature, three refined research questions (RQ) were developed. These questions were framed using the Population, Intervention, Comparison, Outcomes, and Context (PICOC) criteria (Kitchenham & Charters, 2007) to ensure clarity and relevance. To provide clarity and structure, the RQ can be presented as follows:

- **RQ 1**: How was PBL implemented in science education across different countries and educational contexts, and what variations existed in its application?
- **RQ 2**: What were the learning outcomes of PBL in science education globally—including cognitive outcomes, affective outcomes, and skill-based outcomes?
- **RQ 3**: What were the key factors influencing the effectiveness of PBL in science education across various countries, and how did these factors interact to shape its success or limitations?

Method

We aimed to provide a comprehensive summary of the existing research on our RQ through a Systematic Literature Review (SLR). The SLR focused on studies that had undergone rigorous peer-review processes for quality assurance. To address the RQ effectively, we included only journal articles. Studies published as proceedings, book chapters, or other formats were excluded due to their limited scope, lack of detailed findings, and insufficient data to evaluate trends, findings, results, and outcomes comprehensively. This approach ensured a balance between depth of coverage and quality.

The PRISMA guidelines (Page et al., 2021) were followed to enhance transparency and reporting in the selection process, as outlined in Figure 1.

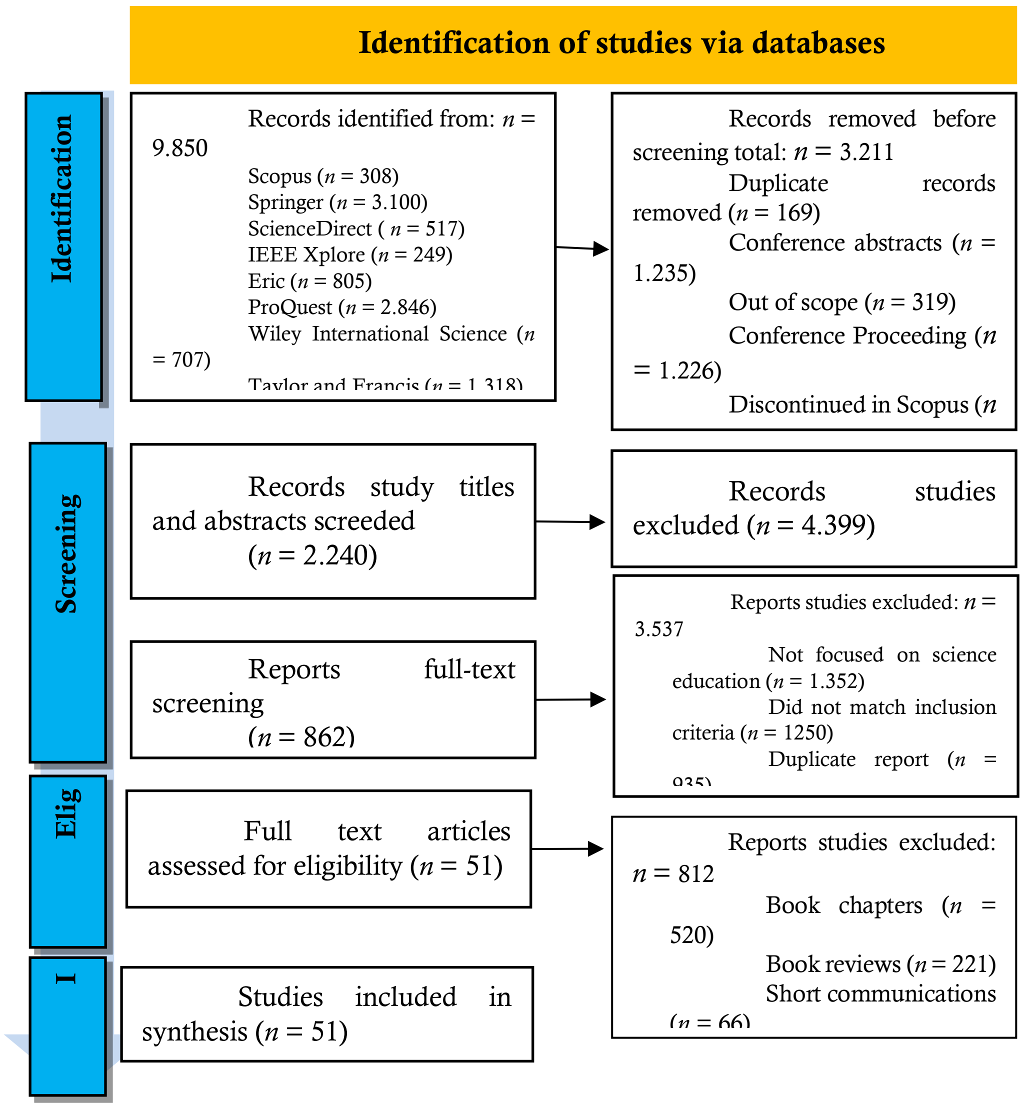


Figure 1. PRISMA Flow Diagram Illustrating Identification and Screening Process

Search Strategy

The search was conducted using electronic databases covering the period from 1965 to December 2022, reflecting the origin of PBL at the McMaster School of Medicine in Canada in 1965 (Tan, 2003; Walton & Matthews, 1989). Although the search does not include the most recent publications, it provides a comprehensive historical and contemporary overview of PBL research. We will consult the journal editors to determine whether an updated search is required, given the increasing number of PBL-related studies published in recent years. The list of databases used in this review includes:

- IEEE Xplore (https://ieeexplore.ieee.org)
- ScienceDirect (https://www.sciencedirect.com)

- ERIC (https://eric.ed.gov)
- Springer (https://link.springer.com)
- Scopus (https://www.scopus.com)
- ProQuest (http://www.proquest.com)
- Wiley International Science (http://onlinelibrary.wiley.com)
- Taylor and Francis (https://www.tandfonline.com)
- Web of Science (https://www.webofscience.com)
- APA PsycInfo (https://psycnet.apa.org)

The database search was carried out through the digital resources of the Universitas Sebelas Maret Library, Indonesia, on September 23, 2022. To ensure comprehensive coverage, the search strings included combinations of key terms and Boolean operators: (a) "Problem-Based Learning" AND "Science"; (b) "Problem-Based Instruction" AND "Science"; (c) "Problem-Based Learning" AND "STEM"; (d) "Problem-Based Learning" AND "Science Education"; and (e) "Problem-Based Instruction" AND "Natural Science." Search strings were adapted for each database's interface while maintaining logical consistency. Articles were identified based on their titles, abstracts, or subject terms containing these key phrases. Additional terms related to STEM education were included to broaden the scope. Figure 1 presents the final set of search strings used in the review.

Screening of Study Based on Inclusion and Exclusion

Four authors independently screened the titles and abstracts of all references identified. Interrater agreement during this initial screening phase was high, with a consistency rate of approximately 94%. Potentially relevant systematic reviews and primary studies were then reviewed in full text. Disagreements were resolved through discussions until consensus was reached. The Mendeley software (http://mendeley.com) was used to manage search results. The PICOC framework guided the inclusion and exclusion criteria, as summarized in Table 1.

Characteristics of PICOC*	**Inclusion**	**Exclusion**
Participants	Science education; Secondary education; Undergraduate science	Studies outside science education; Non-science disciplines
Publication	Peer-reviewed journal articles in English; 1965-2022	Conference proceedings, book chapters, non-peer-reviewed works
Intervention	Studies explicitly involving PBL, identified through a clear description of PBL principles, procedures, or implementation steps within the instructional design.	Interventions not aligned with the definition of PBL
Comparison	Other teaching methods	Studies without comparator
Outcomes	Objective outcomes	Subjective outcomes
Context	Empirical and analytical studies focusing on experimental methods	Non-English studies

*Note. Population, Intervention, Comparison, Outcomes, and Context (PICOC)

Table 1. PICOC Framework for Structuring Research Questions (RQ) and Analysis

Study Quality Assessment

To evaluate the methodological rigor of the included studies, we used quality assessment criteria adapted from Guyatt et al. (2014). Table 2 summarizes the criteria applied. A minimum quality score of 60% was required for inclusion in the review. Interventions that did not align with the definition of PBL were excluded. The interrater reliability for quality coding of articles was assessed, yielding an agreement score of 0.85.

Criteria	**Response grading**	**Acceptance of the included articles (%)**
Are the research questions clearly formulated?	[0, 1, 2] (No, Nominally, Yes)	79%
Does the study context provide adequate explanation?	[0, 1, 2] (No, Nominally, Yes)	77%
Are findings clearly articulated and structured?	[0, 1, 2] (No, Nominally, Yes)	78%
Do outcomes enrich understanding of PBL in science?	> 80% = 1, < 20%, and in-between = 0, 5	76%

Table 2. Quality Criteria for Study Selection

Data Extraction, Mapping, and Analysis

Data extraction followed a multi-stage process to minimize bias. Each study was coded according to the categories outlined in Table 2. Key outcomes, such as the variability of PBL implementation, learning outcomes, and factors influencing success, were systematically mapped. Coding and classification were conducted collaboratively by the four authors and verified through multiple meetings to ensure consistency. Extracted data were organized into a matrix to facilitate analysis and graphical representation of trends. Discrepancies during coding were resolved through discussions. The coding process involved four authors who independently assessed articles. Agreement was evaluated, with 94% of the included studies showing inter-rater consistency. This robust agreement underscores the reliability of the review process.

Classification Scheme

Articles were categorized based on (a) variability of PBL implementation across countries and contexts; (b) measured impacts of PBL, including learning outcomes and assessment methods; (c) key factors influencing success or failure; (d) comparative effectiveness of PBL relative to other teaching methods; and (e) the role of technology in PBL implementation. This classification provided quantifiable insights and ensured the inclusion of studies aligning with the RQ. The final dataset comprised 51 studies for detailed analysis.

Results and Discussion

Characteristics of Included Studies

The results of the search for research papers conducted in the context of the global instructional impact of PBL in science learning showed interesting patterns related to the geographical distribution of research. Since 1998, more studies have been published, indicating that more recent and pertinent studies have been included. Also, Figure 2 shows the relevance of the study of PBL today.

The classification of the data revealed that most of the studies were conducted in Asia (n = 29), Europe (n = 9), Australia (n = 4), North America (n = 3), and South America (n = 2). This pattern showed a significant dominance of PBL-related research in the context of science learning in the Asian region, followed by smaller contributions from other regions such as Europe, Australia, North America, and South America. The data classification results indicated a tendency to focus research on certain geographical areas in the context of the implementation and influence of PBL in science learning. The characteristics included in this study are presented in detail in Appendix A.

Across the selected studies, implementation duration varied widely, ranging from short to long-term courses (Figure 3). The majority of studies (48.8%) were in the long course category (> 3 months); 20.9% were in the medium course category (1 to 2 months); and 30.2% were in the short course category (< 1 month). This finding indicated a tendency to conduct research over a longer period (> 3 months), allowing for a more in-depth analysis of the implementation and impact of PBL in science learning. Although studies of short duration were conducted, they provided an initial look into the implementation of PBL. The distribution of research time highlighted the preference for longer studies but also emphasized the importance of including shorter studies in understanding the implementation of PBL in science learning contexts. According to the data collected (see Figure 2 to Figure 4), the majority of studies used samples between 51 to 100 (n = 14), < 50 participants (n = 9), and > 250 participants (n = 5). This finding indicated a tendency to choose relatively large sample sizes in research on the implementation of PBL models in science learning. Large sample sizes are considered more representative and tend to produce more robust findings in general (Cascella et al., 2020; Creswell, 2012).

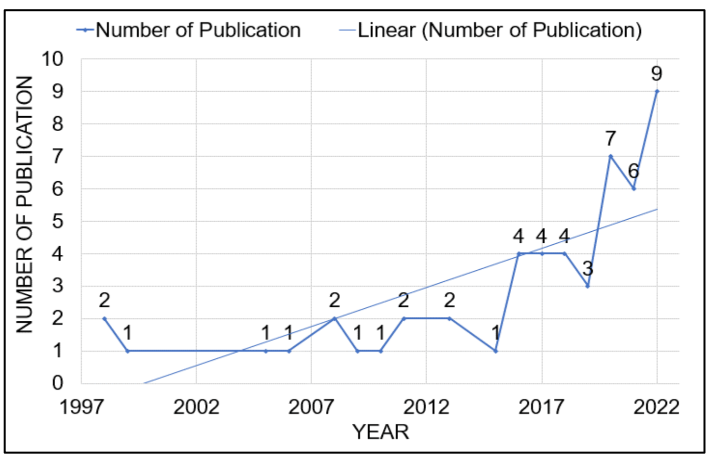


Figure 2. Number of Papers by Year of Publication

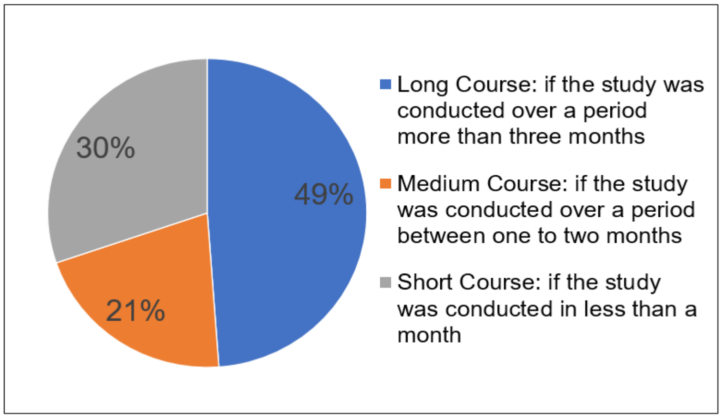
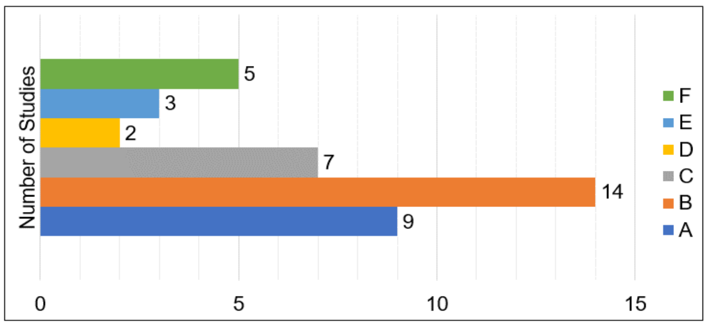


Figure 3. Duration of Study



Notes: A: N≤50; B: 51=N≤100; C: 101=N≤150; D: 151=N≤200; E: 201=N≤250; F: >250

Figure 4. Sample size of participants

RQ 1: How is PBL implemented in science education across different countries and educational contexts, and what variations exist in its application?

PBL is widely applied in various countries and educational contexts and is proven effective in enhancing students' critical thinking, collaboration, and problem-solving skills. The results of research in Turkey showed that the PBL model was more effective in improving students' academic achievement compared to the usual curriculum in junior secondary education (Inel & Balim, 2010). Meanwhile, in Indonesia, PBL aided by a Physics Education Technology (PhET) simulation in a physics class enhanced students' critical thinking skills (Akhdinirwanto et al., 2020). In Malaysia, PBL was applied with positive results, enhancing students' scientific knowledge and creativity (Siew & Mapeala, 2016). Similarly, in Taiwan, the application of AI-based PBL showed improvements in problem-solving skills and learning outcomes (Su, 2022).

The study by Tosun and Yasar (2013) states that PBL facilitates active learning, which enhances critical thinking skills and reflection, contributing to better academic achievement. Research by Gijbels et al. (2005) confirmed that PBL can enhance analytical and problem-solving abilities as students work in groups to explore complex and in-depth problems. Although PBL has been proven effective in many studies, some challenges must be considered. Moreover, the application of technology in PBL, as found in some studies (Setyawan et al., 2020), requires adequate infrastructure readiness to function well in improving scientific literacy. Overall, although there are variations in the results of PBL implementation across countries and educational levels, it can be concluded that PBL has a positive impact on critical thinking, collaboration, and problem-solving skills, especially when supported by appropriate technology and resources.

Variations in PBL implementation across countries differ in duration, educational level, technological integration, and methodological approaches, which in turn influence its effectiveness. In Indonesia, PBL has been implemented at the junior high and higher education levels with durations ranging from two to eight weeks (Mundilarto & Ismoyo, 2017; Putranta et al., 2019). In Malaysia, PBL at primary and secondary levels often integrates collaborative and technology-based approaches (Wan Husin et al., 2016; Siew & Mapeala, 2017), while in Turkey, technology-supported PBL, such as augmented reality, has demonstrated significant improvements in secondary students' academic achievement (Tosun & Yasar, 2013). In Taiwan, AI-based PBL has been employed to enhance problem-solving skills in digital learning environments (Su, 2022). Previous studies indicate that these variations are shaped by cultural context, resource availability, and educational objectives (Dochy et al., 2003; Gao et al., 2022; Liu & Pásztor, 2022; Sharma et al., 2023). Although PBL is highly flexible and adaptable across educational settings, its implementation in Indonesian higher education remains constrained by limited time and technological infrastructure, hindering the effectiveness of blended PBL approaches.

The application of PBL exhibits fundamental differences between primary, secondary, and tertiary education levels, which are reflected in different methods, duration, and learning objectives. At the primary education level, as seen in Malaysia (Musalamani et al., 2021) and Turkey (Inel & Balim, 2010), PBL was often applied with a more structured approach and focused on developing basic skills, such as problem solving, communication, and collaboration. At the secondary level, as demonstrated in Indonesia (Marnita et al., 2020) and Turkey (Fidan & Tuncel, 2019), PBL began to integrate technology and emphasized the improvement of critical thinking skills and scientific literacy. In tertiary education contexts, as seen in Indonesia (Marthaliakirana et al., 2022) and Taiwan (Su, 2022), PBL was intentionally focused on developing more complex academic skills: information synthesis; research; and the application of theory in real-world contexts, often supported by advanced technologies, such as simulation or AI. Based on previous research, the fundamental difference in the application of PBL between educational levels lies in the learning objectives to be achieved.

PBL objectives vary across educational levels. In secondary education, PBL emphasizes the development of critical thinking and problem-solving skills through more open and interactive learning, while in higher education, the approach focuses on analysis, synthesis, and the application of knowledge in complex, professional contexts. Studies indicate that problem complexity in PBL is adaptable to educational levels, ranging from everyday, simple problems in primary education to scientifically and professionally oriented problems in secondary and higher education (Aslan, 2021; Gholami et al., 2016). Despite these differences, common challenges persist across levels, particularly teacher readiness and infrastructure. In Indonesia, limitations in time and technology have constrained PBL implementation in primary and secondary education despite positive effects on scientific skills (Bachtiar et al., 2018), while student readiness for complex self-directed learning remains a key challenge in higher education.

Local and cultural characteristics play a significant role in shaping PBL implementation, influencing teaching approaches, social interaction, and technology use. In Indonesia, PBL is often adapted to cultural values emphasizing gotong royong and group collaboration in primary and secondary education. Likewise, technology-supported collaborative models such as Collaborative Problem-Based Learning (CPBL) align well with the strong cooperative learning culture of Malaysia (Bachtiar et al., 2018). In Turkey, the integration of augmented reality in PBL reflects a local emphasis on innovation and technology to enhance student engagement (Fidan & Tuncel, 2019). Studies suggest that local culture shapes classroom interaction patterns, levels of student engagement, and the degree of autonomy in PBL, particularly in contexts in which hierarchical values and reliance on authority may constrain student independence.

Meanwhile, in contexts that emphasize collaborative learning and open discussion, PBL more strongly supports student autonomy and group problem solving, as demonstrated in Malaysia and

Turkey, where technology-enhanced collaboration aligns with local social and cultural characteristics (Siew & Mapeala, 2016). Although cultural norms (such as respect for teacher authority in Indonesia) may initially limit student autonomy, studies show that integrating technology and collaborative strategies within PBL can enhance student engagement and reduce cultural barriers (Akhdinirwanto et al., 2020). Overall, research indicates that with appropriate cultural and technological adjustments, PBL can be effectively implemented across diverse contexts to promote critical thinking and problem-solving skills while remaining aligned with local values.

RQ 2: What were the learning outcomes of PBL in science education globally—including cognitive outcomes, affective outcomes, and skill-based outcomes?

Based on the synthesis of 30 peer-reviewed studies published between 1999 and 2022, the learning outcomes of PBL in science education globally can be systematically grouped into three major domains: cognitive, affective, and skill-based outcomes. The findings are derived directly from the assessment instruments and analytical approaches reported in the reviewed studies (see Appendix B).

Cognitive outcomes represent the most frequently examined learning domain in global PBL research. Across studies conducted in Asia, Europe, and the Middle East, PBL consistently demonstrated positive effects on critical thinking, problem-solving ability, conceptual understanding, scientific literacy, and creativity. Empirical evidence shows that cognitive outcomes were predominantly measured using achievement tests, critical-thinking tests, open-ended problem-solving tasks, and essay-based assessments. For example, Fidan and Tuncel (2019), Inel and Balim (2010), and Tarhan and Acar Sesen (2013) employed multiple-choice achievement tests combined with open-ended questions to assess conceptual understanding and academic achievement. Similarly, studies by Akhdinirwanto et al. (2020), Jatmiko et al. (2018), and Mundilarto and Ismoyo (2017) used essay-type critical-thinking tests and structured worksheets to capture higher-order thinking processes aligned with Bloom's revised taxonomy (C4–C6). Findings across these studies consistently indicate statistically significant improvements in students' cognitive performance following PBL implementation, particularly when compared to conventional instruction.

Affective learning outcomes, although examined less frequently than cognitive outcomes, emerged as a critical dimension of PBL effectiveness. Studies conducted in Malaysia, Turkey, South Korea, and Indonesia reported improvements in student motivation, engagement, attitudes toward science, and learning interest. These outcomes were primarily measured using Likert-scale questionnaires, attitude inventories, and self-report instruments. For instance, Fidan and Tuncel (2019), Jo and Ku (2011), and Tarhan and Acar Sesen (2013) employed attitude and motivation scales to evaluate students' affective responses to PBL environments. Siew et al. (2017) further demonstrated that students' motivation toward science learning significantly increased after an 18-hour PBL intervention, as measured by the Students' Motivation Towards Science Learning (SMTSL) questionnaire. The consistent finding across affective-focused studies is that PBL fosters positive emotional engagement and intrinsic motivation, particularly when learning activities involve authentic problems, collaborative inquiry, and student autonomy.

Skill-based outcomes constitute the third major category of learning outcomes reported in global PBL studies, with a strong emphasis on collaboration, communication, creativity, and scientific inquiry skills. These outcomes were especially prominent in studies conducted at the primary and secondary education levels. Assessment of skill-based outcomes relied heavily on performance-based instruments, including rubrics, portfolios, observation sheets, oral presentations, laboratory evaluations, and peer assessments. For example, Hoermann et al. (2022), Hugerat et al. (2021), and Musalamani et al. (2021) assessed collaboration and communication skills through portfolio-based evaluation and student presentations, while Setyawan et al. (2020) used scientific communication assessment sheets and student research reports to evaluate inquiry competence. Findings indicate that

PBL significantly enhances students' ability to work collaboratively, communicate scientific ideas effectively, and engage in creative problem solving, particularly in learning environments that emphasize group investigation and open-ended inquiry tasks (Nuswowati et al., 2017; Siew et al., 2015).

RQ 3: What are the key factors influencing the effectiveness of PBL in science education across various countries, and how do these factors interact to shape its success or limitations?

Based on the cross-study synthesis presented in Appendix A, the effectiveness of PBL in science education is shaped by a set of interrelated factors that consistently emerge across countries and educational contexts. Rather than operating independently, these factors interact to either enhance or constrain the impact of PBL on student learning outcomes. The dominant factors identified include teacher readiness and facilitation competence, instructional design of problems, technology support, student engagement and collaboration, and contextual support such as educational policy and local culture.

Teacher readiness and facilitation competence consistently emerge as the most influential factors in effective PBL implementation. Studies in Indonesia highlight the central role of teachers in managing group dynamics and guiding independent problem solving (Setyawan et al., 2020). Technology integration, such as the use of augmented reality in Turkey, has been shown to significantly enhance student achievement by enriching learning resources and engagement (Fidan & Tuncel, 2019). Moreover, social and cultural support contributes to improved collaborative skills and motivation, as evidenced in Malaysia (Siew & Mapeala, 2016). However, limited time, resources, uneven teacher training, and insufficient policy support remain key challenges that can reduce PBL effectiveness, especially in resource-constrained contexts (Hammond, 2014; Lonergan et al., 2022; Suryawati & Osman, 2018).

The readiness of teachers, technology support, and student engagement are interacting factors that have a great influence on the success of PBL implementation in science education. Based on research conducted in several countries, teacher readiness in implementing PBL is closely related to the effectiveness of the PBL model. In Indonesia, studies show that teachers who have specialized training in PBL are more effective in managing the classroom and providing appropriate guidance during the PBL process (Hendarwati et al., 2022).

Technological support and teacher readiness are key enablers of effective PBL implementation. Studies in the United States show that digital platforms and interactive tools enhance conceptual understanding and critical thinking (Cheaney & Ingebritsen, 2006), while findings from Barcelona indicate that active participation in group discussion and shared decision making improves problem-solving outcomes (Carrió et al., 2016). Effective PBL facilitation requires teachers' pedagogical competence in managing classroom dynamics, fostering discussion, and providing constructive feedback (Perusso & Leal, 2022; Su, 2022). Technology further enriches learning through broader access to resources, simulations, and visualizations, particularly in science education (Aslan, 2021; Lonergan et al., 2022). High levels of student engagement are essential, as they directly contribute to the development of critical and collaborative thinking skills (Affandy et al., 2024). Nevertheless, disparities in technological access and limited teacher time for instructional design remain persistent challenges in PBL implementation.

Educational policies and local culture substantially influence the effectiveness of PBL implementation across contexts. Policies that support pedagogical innovation, instructional flexibility, and teacher training (such as those in Indonesia) enable more contextualized and effective PBL practices (Suryawati et al., 2020). Local cultures that emphasize cooperation further strengthen PBL by promoting active collaboration, social interaction, and the development of critical thinking skills (Varas et al., 2023). In contrast, limitations in infrastructure, regional educational inequality, and insufficient resources for teacher development can hinder PBL implementation (Al-Ismaily et al., 2023; Peng, 2023). Overall, evidence indicates that supportive policies combined with collaborative cultural contexts significantly enhance the effectiveness of PBL, particularly in science education (Agbo et al., 2023; Van Hooijdonk et al., 2023).

Research in resource-limited contexts, such as Indonesia and other developing countries, identifies inadequate technological infrastructure, limited teacher training, and insufficient access to quality learning materials as the main barriers to effective PBL implementation. Despite supportive education policies, many Indonesian schools lack technological devices and professional development opportunities, while constrained education budgets limit the provision of appropriate PBL resources (Parno et al., 2020). These constraints hinder teachers' ability to facilitate collaboration and interaction essential to PBL. Nevertheless, evidence shows that creative strategies (such as utilizing locally available materials and adopting low-cost technologies like mobile devices and simple applications) can partially mitigate these challenges and support PBL implementation in resource-constrained settings.

Implications for Instructional Design and Practice

The findings highlight important implications for instructional design and practice in science education. While PBL has been shown to enhance students' critical thinking, collaboration, and problem-solving skills across contexts, its effectiveness depends on instructional designs that integrate technology, adapt learning materials to local conditions, and ensure adequate teacher preparation and resource use. Instructional design should therefore be flexible and context-responsive, considering cultural values, socio-economic conditions, and levels of technological access. PBL designs that emphasize collaboration and group problem solving are more effective, whereas in more individualistic settings, greater opportunities for independent inquiry are required. Additionally, in resource-limited or rural contexts, the selection of authentic problems, use of locally available materials, and adoption of low-cost technologies are essential to support effective PBL implementation.

Limitations and Future Work

The limitations of this study have potential to be a key focus for future studies to expand the understanding of PBL implementation in science learning. One limitation was found in the geographically and contextually limited scope of the data, resulting in a limited understanding of the variations of PBL around the world. Future studies could complement by involving more countries and different educational contexts, including environments that may have unique challenges related to infrastructure, culture and educational policies. However, the limitations in measuring the impact of PBL on student engagement and critical skills development are a focus for further research. In addition, future studies could further explore the role of technology in supporting PBL, including the integration of innovative technologies—such as artificial intelligence, interactive simulations, or online learning platforms—to support more effective PBL implementation.

Conclusion

The comprehensive literature review aims to explore the global instructional impact of PBL in science education. Based on the designed inclusion and exclusion criteria, 51 PBL studies published between May 1998 and December 2022 remained and investigated. The application of PBL in science education could enhance students' critical thinking, collaboration and problem-solving skills in different countries, with effectiveness largely dependent on adaptive and context-based instructional design. PBL has been proven to be effective in resource-limited countries when learning materials are adapted to the local context and culture of students. Moreover, the success of PBL is influenced by factors such as teacher training and technology integration, as well as more student-centered teaching approaches and more holistic evaluation. Adjustments in teaching approaches and evaluation techniques, such as project-based assessment and utilization of digital platforms, are also important to support students' active engagement in the learning process. Cultural and social diversity affect the way students interact with learning; therefore, instructional design must consider these aspects to increase the effectiveness of PBL. The research findings guide the development of a more adaptive science curriculum by integrating PBL more widely across different levels of education and introducing learning strategies that are relevant to local conditions and existing resources.

Acknowledgments

The authors would like to express their sincere appreciation to Universitas Indonesia Mandiri and Universitas Sebelas Maret for their institutional support throughout the completion of this study. The authors also extend their gratitude to colleagues and reviewers who provided valuable feedback during the development of this manuscript. No external funding was received for this research. The authors are solely responsible for the content of this article.

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Appendix A

Characteristics of Included Studies

Primary Studies	Country	Participants	Methods of Research	Sample Size	Duration of Intervention	Findings
Inel & Balim, 2010	Turkey	Lower secondary education	Experimental approach	41	4-week quasi-experimental application	The problem-based learning method in science and technology teaching is more effective in enhancing students' academic achievement than simply using the science and technology curriculum.
Özlem et al., 2008	Turkey	Primary education	Experimental approach	85	Four 50-minute sessions per week	Problem-based learning developed problem-solving skills of pre-service elementary school teachers while enhancing their communication, group working skills and acquisition of knowledge.
Siew & Mapeala, 2016	Malaysia	Lower secondary education	Ene group quasi-experimental	125	6 days	Problem Oriented Project Based Learning (POPBL) provides opportunities for students to apply their knowledge and simultaneously encourages them to gather information.
Bahri et al., 2021	Indonesia	Undergraduate degree	Quasi-experimental design	72	1 semester	PBL did not appear to effectively promote students' character development during the instructional implementation, as observations conducted during laboratory sessions indicated variability in students' character-related behaviors.
Akhdinirwanto et al., 2020	Indonesia	Upper secondary education	Research and development	62	N/A	PBL learning devices assisted by Physics Education Technology (PhET) simulations developed meet the eligibility requirements for use in physics learning activities using PBL learning models to improve students' critical thinking skills in work and energy chapters.
Fidan & Tuncel, 2019	Turkey	Lower secondary education	Quasi-experimental	91	11 weeks	The experimental results of this study demonstrated that the students who used augmented reality (AR) technology in the PBL process had significantly higher learning achievement scores when compared with both only PBL and teacher-based instruction in the classroom.
Hendarwati et al., 2022	Indonesia	Lower secondary education	Mixed methods	60	2 weeks	PBL had a significant effect on increasing metacognitive abilities in the conjecturing process.
Sakir & Kim, 2020	South Korea	Lower secondary education	Action research	24	2 months (six meetings)	Increasing student learning activity and outcomes revealed a positive impact of the PBL approach, as the students in the classroom were required to seek a solution based on the existing problems in the worksheets.
Marthaliakirana et al., 2022	Indonesia	Upper secondary education	Quasi-experimental	121	2 weeks	After the intervention, metacognitive prompts (M-PBL) students' argumentation scores were significantly higher than those of high-intensity problem-based learning (H-PBL) and low-intensity problem-based learning (L-PBL), indicating they had improved their ability to construct arguments, particularly warrants, reasoning, and more complex fully fledged arguments.
Hugerat et al., 2021	Israel	Upper secondary education	Quasi-experimental	106	3 months	Teachers facilitated the learning process by guiding the students through the various stages of Problem-Based–Jigsaw Discussion (PBL-JD), by connecting them to the problem, building the structure, visiting and revising the problem, creating a product and presenting and evaluating the implementation.
Jatmiko et al., 2018	Indonesia	Undergraduate degree	Quasi-experimental	N/A	2–3 weeks	One active classroom method known as problem-based learning promotes self-motivated learning and synthesis skills that, when applied in a science-literacy context, can provide students with the ability to generate informed opinions on new scientific advances throughout their lifetime.
Nawi et al., 2019	Malaysia	Lower secondary education	Qualitative study	82	1- to 2-hour sessions, approximately twice a month	Using Low Carbon Society (LCS) program as the theme in formal education using Cooperative Problem-Based Learning (CPBL) with Technology Enhanced Learning (TEL), it helps the students to gain broader knowledge, awareness, exposure and instil strong conviction towards making LCS a reality in the future.
Poonsawad et al., 2022	Thailand	Undergraduate degree	Quasi-experimental	90	4 weeks, from March 2021 to April 2021	Problem-based interactive digital storytelling learning model group (S2) exhibited the highest academic achievement (M = 60.14, SD = 1.88). Interestingly, S1's traditional classroom methods scored higher for academic achievement than the PBL group (S3).
Ernawati et al., 2022	Indonesia	Undergraduate degree	Quasi-experimental design	44	2–3 weeks	Implementing integrated problem-based learning model with scaffolding in online learning was effective for improving collaborative and problem-solving skills for students at the tertiary level during the COVID-19 pandemic.
Marnita et al., 2020	Indonesia	Undergraduate degree	Quasi-experimental	72	2–3 weeks	• Improved mental models of students with high early capability who learn by PBL is higher than students learning with conventional learning. • Improvement of low-skilled student mental models learning with PBL is higher than students learning with conventional learning.
Cheaney & Ingebritsen, 2006	United States of America	Undergraduate degree	Experiment	30	1 semester; 5-week unit about genetic testing technologies	A problem with this approach is the difficulty of scheduling synchronous meetings. Problems here include typing abilities (especially speed) and the ability to decipher multiple simultaneous threads of conversation.
Su, 2022	Taiwan	Undergraduate degree	Mixed-method	127	2 semesters	Artificial Intelligence Problem-Based Learning (AI-PBL) teaching contexts helped most students enrich learning connotations, nurture problem-solving thinking, and enhance their learning levels through interaction and guidance.
Siew et al., 2017	Malaysia	Lower secondary education	Quasi-experimental	270	9 weeks	Thinking Maps-aided Problem-based Learning teaching method (TM-PBL) gained significantly higher levels than their counterparts from the PBL group in self-efficacy, active learning strategies, achievement goal, and learning environment stimulation.
Bachtiar et al., 2018	Indonesia	Undergraduate degree	Quasi-experimental	94	3 weeks	Physics teaching process with problem based learning (PBL) model is more effective in improving student critical thinking skills when compared to Numbered Heads Together (NHT).

Primary Studies	Country	Participants	Methods of Research	Sample Size	Duration of Intervention	Findings
Musalamani et al., 2021	Malaysia	Lower secondary education	Quasi-experimental	120	6 weeks	The School Based-Cooperative Problem-Based Learning (SB-CPBL) students emerged as active learners, engaging in a safe learning environment where they are actively engaged in group discussions, peer dialogues, and are unafraid to ask questions or dissect ideas.
Tosun & Yasar, 2013	Turkey	Upper secondary education	Quasi-experimental	108	4 week	Problem Based Learning Assessment Scale (PBLAS) results reflected that students' positive beliefs increased after each activity. Based on these results, PBL instruction appears to be effective in concept learning in chemistry education.
Carrió et al., 2016	Barcelona	Undergraduate degree	Quasi-experimental	85	PBL tutorials were carried out in groups of eight to ten students during the full academic year (9 months)	Hybrid problem-based learning (H-PBL) curriculum implemented in our school improved factual knowledge acquisition of students in the long term.
Wan Husin et al., 2016	Malaysia	Primary education	Quasi-experimental	4530	9 weeks	Students taught via the Project Oriented Problem Based Learning (POPBL) could help students to enhance their 21st-century skills by learning how to solve real world problems based on authentic and real life experiences through project work.
Siew & Mapeala, 2017	Malaysia	Primary education	Quasi-experimental	216	6 weeks, with 60 minutes for each activity	Problem based learning with cooperative learning (CL) and Numbered Heads Together (PBL-CLNHT) methods could benefit from the NHT cooperative learning structure to foster their trait dimensions of scientific creativity more effectively, as compared to being taught with only the Problem based learning (PBL) and hands-on (TG) methods.
Nuswowati et al., 2017	Indonesia	Upper secondary education	Quasi-experimental	224	3 weeks	The use of the PBL model employing the method of experiment and the method of demonstration hopefully would bring about a result conforming to an objective of physics learning, namely, making students show scientific behaviour and develop experience in using scientific methods.
Setyawan et al., 2020	Indonesia	Lower secondary education	Quasi-experimental	352	2–3 weeks	The integration of technology within the problem-based learning model has a significant effect on students' scientific communication skills.
Mundilarto & Ismoyo, 2017	Indonesia	Undergraduate degree	Mixed method	38	3 weeks	Improved creative thinking skills are also followed by improvements in other learning outcomes.
Sutarto et al., 2022	Indonesia	Undergraduate degree	Mixed method	173		Learning using this model makes classroom learning more engaging, making students improve communication relationships, analyze problems, and improve student attitudes.
Suryawati et al., 2020	Indonesia	Undergraduate degree	Quasi-experimental	N/A	2 months	Problem-based learning model based on blended learning, namely the average of all initial test items and final test items for pre-service teachers to obtain moderate and high N-Gain scores.
Parno et al., 2020	Indonesia	Upper secondary education	Quasi-experimental non-equivalent group	99	6 weeks	PBL-STEM can improve students' scientific literacy competencies domain better than PBL and conventional learning and that PBL can improve students' scientific literacy competencies domain better than conventional learning.
Putranta et al., 2019	Indonesia	Lower secondary education	Quasi-experimental design pretest-posttest	372	2 months	The ability to analyze and evaluate issues in this study is facilitated by providing discourse, videos of gold mining activities, forest fires, and urban waste.

Appendix B

Learning Outcomes of PBL in Science Education and Their Measurement Across Diverse Educational Contexts

Primary Studies	Publication	Assessment	Findings (Learning Outcomes)
Inel & Balim, 2010	Asia-Pacific Forum on Science Learning and Teaching	11 open-ended concept construction items; 48-item academic achievement test	PBL significantly improved students' conceptual understanding and academic achievement compared to conventional instruction.
Özlem et al., 2008	Asia-Pacific Forum on Science Learning and Teaching	Problem-Solving Skills Inventory (PSSI); interviews; open-ended questionnaire	Students in PBL showed higher problem-solving skills and deeper reasoning processes.
Wan Husin et al., 2016	Asia-Pacific Forum on Science Learning and Teaching	Questionnaire	PBL positively influenced students' learning engagement and attitudes toward science.
Bahri et al., 2021	Asia-Pacific Forum on Science Learning and Teaching	MC tests (70 items); character questionnaire; observation sheet	PBL enhanced cognitive achievement and positive character-related behaviors.
Putranta et al., 2019	Asia-Pacific Forum on Science Learning and Teaching	5 open-ended HOTS items (C4–C6)	Students demonstrated improved higher-order thinking skills, particularly analysis and creativity.
Fidan & Tuncel, 2019	Computers & Education	Achievement test; attitude scale	AR-supported PBL significantly increased academic achievement and learning attitudes.
Sutarto et al., 2022	Education Research International	Problem-solving tests; interviews	PBL improved students' problem-solving ability and conceptual reasoning.
Sakir & Kim, 2020	EURASIA Journal of Mathematics, Science and Technology Education	Observation data; learning outcomes	Students showed improved learning participation and science achievement after PBL implementation.
Marthaliakirana et al., 2022	EURASIA Journal of Mathematics, Science and Technology Education	Mutiple choice test; argumentation essay	PBL enhanced critical thinking and scientific argumentation skills.
Hugerat et al., 2021	EURASIA Journal of Mathematics, Science and Technology Education	Questionnaires; portfolio; presentation	Students developed stronger inquiry, collaboration, and communication skills.

Primary Studies	Publication	Assessment	Findings (Learning Outcomes)
Nantha et al., 2022	International Journal of Emerging Technologies in Learning	Formative and summative essay assessment	Students achieved better conceptual understanding and reflective thinking.
Hendarwati et al., 2022	International Journal of Emerging Technologies in Learning	Collaborative questionnaire; essay tests	PBL improved collaborative skills and problem-solving performance.
Batlolona, 2020	International Journal of Evaluation and Research in Education	Diagnostic test	PBL facilitated conceptual change and reduced misconceptions.
Cheaney & Ingebritsen, 2006	The International Review of Research in Open and Distributed Learning	Essay; portfolio	Students demonstrated improved reflective thinking and independent learning skills.
Siew et al., 2015	Journal of Baltic Science Education	Scientific creativity tests	PBL enhanced students' scientific creativity and originality.
Ram, 1999	Journal of Baltic Science Education	Self-evaluation; oral presentation; lab evaluation	PBL strengthened practical skills, communication, and self-reflection.
Su, 2022	Journal of Baltic Science Education	Open-ended tests	Students achieved deeper conceptual understanding through PBL.
Siew et al., 2017	Journal of Baltic Science Education	Students' Motivation Towards Science Learning (SMTSL) questionnaire	PBL significantly increased students' motivation toward science learning.
Jatmiko et al., 2018	Journal of Baltic Science Education	Essay-based Critical Thinking test	PBL improved critical thinking skills of pre-service physics teachers.
Musalamani et al., 2021	Journal of Baltic Science Education	Questionnaires; portfolio; presentation	Students showed better collaboration, communication, and inquiry skills.
Tarhan & Acar Sesen, 2013	Journal of Baltic Science Education	Achievement test; belief scale	PBL enhanced academic achievement and positive beliefs about learning science.
Carrió et al., 2016	Journal of Baltic Science Education	Knowledge and problem-solving questionnaire	Students demonstrated higher factual knowledge and problem-solving skills.
Siew & Mapeala, 2016	Journal of Baltic Science Education	Test of Science Critical Thinking (TSCT)	PBL significantly improved multiple dimensions of critical thinking.
Siew et al., 2017	Journal of Baltic Science Education	Figural Scientific Creativity Test	PBL fostered scientific creativity and divergent thinking.
Mundilarto & Ismoyo, 2017	Journal of Baltic Science Education	Mutiple choice test; essay test	Students achieved higher conceptual mastery and reasoning ability.
Setyawan et al., 2020	Journal of Technology and Science Education	Worksheets; reports; questionnaires	PBL improved scientific communication, inquiry skills, and cognitive outcomes.
Nuswowati et al., 2017	Jurnal Pendidikan IPA Indonesia	Creative thinking & attitude tests	PBL enhanced creative thinking skills and creative attitudes.
Ernawati et al., 2022	Jurnal Pendidikan IPA Indonesia	Essay test; questionnaire	Students showed improved creative thinking and positive learning responses.
Marnita et al., 2020	Jurnal Pendidikan IPA Indonesia	Critical Thinking skills test	PBL contributed to higher critical thinking performance.
Parno et al., 2020	Jurnal Pendidikan IPA Indonesia	Scientific literacy test	PBL improved students' scientific literacy.
Suryawati et al., 2020	Jurnal Pendidikan IPA Indonesia	Mutiple Choice test; questionnaire	PBL increased academic achievement and learning motivation.
Akhdinirwanto et al., 2020	Jurnal Pendidikan IPA Indonesia	Activity & assessment sheets	PBL enhanced critical thinking and active student engagement.