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Implementation of problem-based learning and the challenges in science education: A systematic literature review

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Abstract

Background: Problem-Based Learning, PBL, is a student-centered approach in science education that promotes conceptual understanding and higher-order thinking by engaging learners with authentic contextual problems.
Aims: This systematic review synthesizes how PBL is implemented in science education, what outcomes are most frequently reported, and what barriers commonly hinder its adoption.
Method: A PRISMA-guided systematic literature review was conducted using Scopus. Searches employed the terms “problem-based learning,” “science education,” and “science learning.” Eligible studies were empirical journal articles and conference proceedings published from 2017 to August 2025, written in English, and involving participants from elementary school through higher education. Of 388 records identified, 53 studies met the inclusion criteria and were analyzed according to publication trends, research designs, implementation strategies, targeted outcomes, and reported constraints.
Results: Across educational levels, PBL was consistently associated with cognitive gains, especially in critical thinking, problem solving, and higher-order thinking skills. The reviewed evidence also indicated affective benefits, including stronger scientific attitudes, improved learning motivation, and enhanced collaboration. Nevertheless, recurring challenges emerged, such as limited instructional time, demanding assessment processes, curriculum coverage pressures, uneven teacher readiness, unequal participation in group work, and gaps in access to learning resources and technology.
Conclusion: PBL offers clear promise for improving both cognitive and affective dimensions of science learning, yet its success depends on well-designed contextual problems, adequate pedagogical support, and alignment with learners’ readiness. Strengthening teacher capacity and refining assessment practices are essential to reduce persistent implementation barriers.

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INTRODUCTION

In recent years, science education has increasingly shifted toward contextual and student-centered approaches (Bhardwaj et al., 2025; Morris, 2025). This shift reflects the recognition that meaningful science learning cannot rely solely on procedural delivery of concepts, but must connect scientific knowledge to situations that are relevant to students’ lived experiences (T. Li et al., 2024; Pellas, 2025). When learners are confronted with meaningful problems, they are encouraged to interpret information, evaluate alternative explanations, and construct evidence-based reasoning (Csanadi et al., 2021; Siverling et al., 2021). In this context, the use of multiple forms of representation, including visual models, diagrams, written explanations, and symbolic expressions,

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plays an essential role in supporting deeper conceptual understanding and strengthening problem-solving abilities.

Problem-Based Learning, PBL, is widely recognized as an instructional approach that places authentic problems at the center of the learning process (Smith et al., 2022; Taconis & Bekker, 2023). Rather than positioning students as passive recipients of information, PBL encourages them to identify issues, gather and evaluate relevant information, test assumptions, and formulate reasoned solutions through inquiry. This process is typically carried out collaboratively, allowing students to exchange perspectives, justify arguments, and refine their understanding through dialogue (Hähkiöniemi et al., 2022; Rapanta et al., 2021). As a result, PBL emphasizes not only the final solution but also the thinking processes that lead to it (Suradika et al., 2023; Susanti et al., 2023). In science education, such characteristics align closely with the need to foster scientific reasoning, higher-order thinking, and the ability to apply concepts in meaningful contexts.

Conceptually, PBL is grounded in constructivist views of learning, which regard knowledge as something actively constructed through experience and reflection. Learning becomes more effective when students engage with challenging situations that require investigation and thoughtful analysis (Almusaed et al., 2023; Taye & Mengesha, 2024). Therefore, the effectiveness of PBL cannot be reduced to simply following procedural stages or prescribed steps. The quality of problem design, the nature of pedagogical support provided by the teacher, and the dynamics of classroom interaction all play crucial roles in determining learning outcomes (Bhuttah et al., 2024; Zhai, 2025). Successful implementation depends not only on the model itself but also on how it is enacted within specific educational contexts.

A growing body of research reports that PBL has been implemented across various educational levels, from elementary school to higher education, and has generated positive learning outcomes (Wijnia et al., 2024). These outcomes frequently include improvements in conceptual mastery, critical thinking, problem-solving skills, and higher-order thinking abilities (Kania & Kusumah, 2025). In addition to cognitive gains, PBL is often associated with affective benefits, such as the development of scientific attitudes, increased learning motivation, and enhanced collaborative skills (Sukackė et al., 2022; Wijnia et al., 2024). Despite these reported advantages, classroom implementation of PBL is frequently accompanied by recurring challenges. Common obstacles include limited instructional time, pressure to complete curriculum targets, complexity in assessing inquiry-based processes, variation in teacher readiness, differences in students' preparedness for independent and collaborative learning, and constraints related to learning resources and technological access.

Although studies on PBL continue to expand, existing knowledge remains fragmented when examined from an implementation perspective (J. Chen et al., 2021). Many summaries of research emphasize effectiveness or focus on specific outcomes, while providing limited integration of implementation strategies and the practical challenges that influence sustainability (Hallinger, 2021). Furthermore, previous reviews are often restricted to particular disciplines, national contexts, or educational levels, making it difficult to obtain a comprehensive understanding of how PBL operates within science education across the educational continuum (Boelt et al., 2022; Sukackė et al., 2022). This limitation is significant because reported benefits may not be fully realized when implementation barriers are not systematically addressed (Oldemeyer et al., 2025).

In response to this need, the present study conducts a systematic literature review on the implementation of PBL and the challenges associated with its adoption in science education. This review seeks to answer three central questions: what strategies are used to implement PBL in science education, what learning outcomes are most frequently reported, and what challenges consistently emerge across educational contexts from elementary to higher education. By synthesizing empirical evidence in a structured manner, this study aims to provide a clearer and more integrated understanding of how PBL functions in science education and what factors shape its effectiveness and sustainability.

METHOD

Research Design

This study adopted a systematic literature review approach to examine how Problem-Based Learning is implemented in science education and to identify the challenges associated with its adoption. The review was conducted through a structured and transparent procedure designed to ensure methodological clarity and replicability. The overall process of the review is illustrated in Figure 1, which outlines the main stages from defining research questions to synthesizing findings and drawing implications.

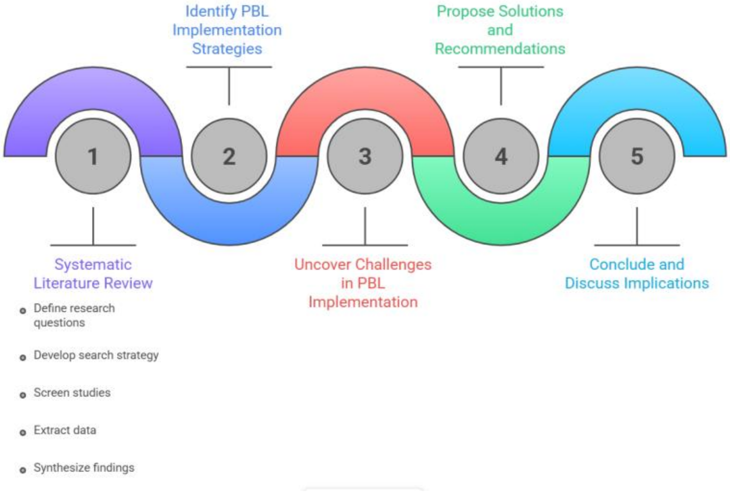

Figure 1. Workflow of the Systematic Literature Review Process

The workflow begins with the formulation of research questions and the development of a search strategy, followed by study identification, screening, eligibility assessment, and final inclusion. Beyond article selection, the process also includes categorizing implementation strategies, identifying recurring challenges, and synthesizing outcomes. To maintain rigor in study selection, the review process was aligned with the PRISMA framework, which structures the review into identification, screening, eligibility, and inclusion stages. This framework ensured that only relevant empirical studies were retained for analysis.

Participants

In this review, the unit of analysis consisted of published empirical studies rather than individual participants. The selected sources included peer-reviewed journal articles and conference proceedings indexed in the Scopus database. To ensure relevance and contemporary coverage, inclusion criteria required that studies be published between 2017 and August 2025, written in English, and conducted within science education contexts ranging from elementary school to higher education. The initial search identified 388 records. After removing duplicates and applying predefined inclusion and exclusion criteria, 53 studies met the eligibility requirements and were included in the final analysis. These studies formed the evidence base for examining patterns of PBL implementation and reported challenges.

Instrument

Data from the selected studies were collected using a structured data extraction framework developed by the researchers. This framework functioned as the primary instrument for organizing and recording relevant information systematically. The extraction process focused on key variables, including year of publication, research design, educational level, subject area within science, variations in PBL implementation strategies, reported learning outcomes, and documented implementation challenges. Using a structured extraction format enhanced consistency across studies and reduced the likelihood of subjective interpretation during the coding process. Each article was reviewed carefully to ensure that the extracted information accurately reflected the original study findings.

Data Analysis

The analysis combined descriptive mapping and thematic synthesis. First, publication trends and research characteristics were summarized descriptively to identify patterns in research design, educational level, and subject focus. Second, implementation strategies were grouped into major categories, such as the use of core PBL syntax, integration with technology-based instructional materials, and combination with other instructional models. Third, reported outcomes were classified into cognitive and affective domains to capture the breadth of learning impacts associated with PBL. Finally, recurring challenges were analyzed thematically and organized into categories related to teacher readiness, student preparedness, curriculum constraints, time limitations, assessment complexity, and availability of learning resources. Through this systematic categorization and synthesis process, the review generated an integrated understanding of how PBL is enacted in science education and what factors influence its effectiveness across educational levels.

RESULTS AND DISCUSSION

Results

Study Selection and Publication Trends

The database search yielded 388 records published between 2017 and August 2025. Following duplicate removal and the application of predefined inclusion criteria, 53 empirical studies were retained for analysis. These studies form the evidence base for examining how Problem-Based Learning has been implemented and what challenges have been documented in science education contexts.

Table 1 presents the annual distribution of eligible studies, while Figure 1 illustrates the overall publication trend.

Table 1. Distribution of Eligible Studies by Publication Year

Year	Eligible Studies
2017	4
2018	5
2019	5
2020	5
2021	9
2022	6
2023	7
2024	7
2025 (Aug)	5
Total	**53**

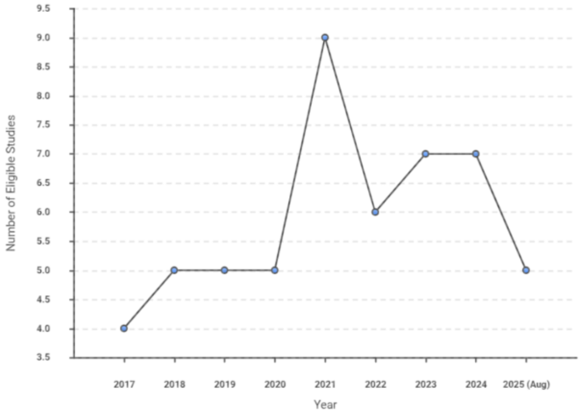

Figure 2. Annual distribution of eligible studies on PBL implementation in science education (2017–August 2025).

As depicted in Figure 2, research on PBL in science education shows a gradual rise from 2017, reaching its highest concentration in 2021. Although the number of publications fluctuated slightly in subsequent years, the pattern does not indicate decline but rather stabilization. This suggests that PBL remains a consistently explored approach within science education research rather than a short-lived trend.

Research Design Characteristics

To better understand methodological tendencies, the selected studies were classified according to research design. The distribution is summarized in Table 2 and visualized in Figure 3.

Table 2. Distribution of Research Design

Research Design	Number of Studies
Quantitative	35
Qualitative	5
Mixed Methods	9
Research and Development	4
Total	**53**

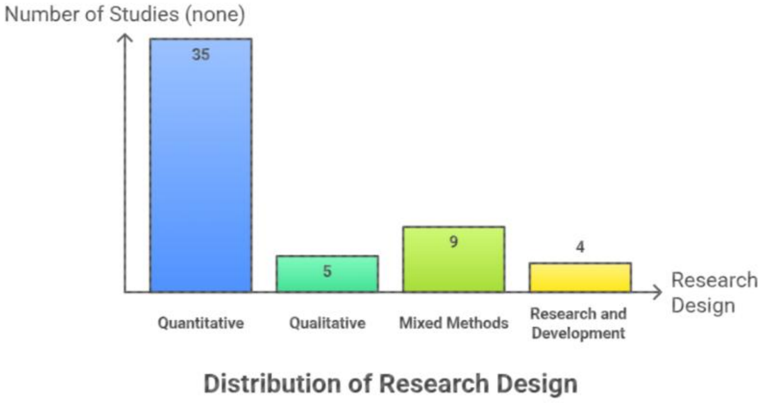

Figure 3. Distribution of research design among the included studies.

The data reveal a clear predominance of quantitative approaches. More than half of the included studies employed statistical methods to measure learning outcomes, indicating a strong emphasis on evaluating effectiveness through measurable indicators. Mixed methods designs appear to bridge numerical and interpretive analysis, although in smaller numbers. Purely qualitative and research-and-development approaches are comparatively limited, suggesting that exploratory and design-focused investigations of PBL are less frequent than outcome-driven studies.

Patterns of PBL Implementation

Across the reviewed literature, three broad patterns of PBL implementation were identified. These patterns are summarized in Table 3.

Table 3. Categories of PBL Implementation Strategies

Implementation Type	Number of Studies
Core PBL Syntax	20
PBL + Technology Integration	14
PBL + Other Learning Models	19
Total	53

The findings indicate that PBL is rarely implemented in a single uniform format. While a number of studies adhered closely to core PBL stages, many integrated digital tools such as online platforms, simulations, or multimedia resources to scaffold inquiry processes. Others combined PBL with complementary models, including STEM-oriented approaches or collaborative learning structures. This variation reflects the adaptability of PBL across instructional contexts and curricular demands.

Reported Learning Outcomes

Learning outcomes reported in the selected studies were categorized into cognitive and affective domains. The detailed distribution is presented in Table 4, and the overall comparison between domains is illustrated in Figure 3.

Table 4. Learning Outcomes in PBL Implementation Studies

A. Cognitive Outcomes (39 studies)

Indicator	Number of Studies
Critical Thinking	15
Concept Mastery	11
Problem-Solving Skills	7
Higher-Order Thinking Skills	3
Creative Thinking	3
Scientific Literacy	3

B. Affective Outcomes (23 studies)

Indicator	Number of Studies
Scientific Attitudes	6
Learning Motivation	5
Collaborative Skills	4
Self-Efficacy	2
SDG Awareness	2
Decision-Making	1
Metacognitive Skills	1

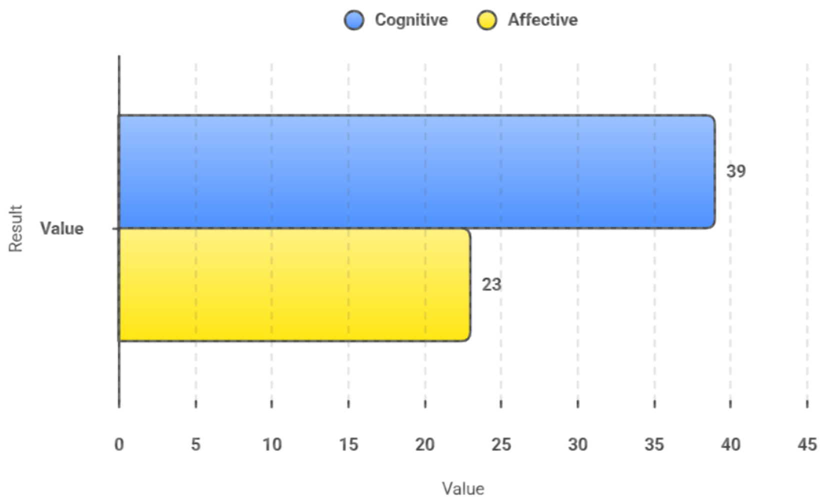

Figure 4. Distribution of reported cognitive and affective learning outcomes in PBL implementation studies.

Figure 4 makes visible the stronger concentration of studies reporting cognitive gains. Critical thinking and conceptual mastery appear most frequently, reinforcing the view that PBL is often evaluated in relation to higher-order cognitive development. Although affective outcomes are reported less often, improvements in scientific attitudes and motivation suggest that PBL also influences learners' dispositions toward science. It should be noted that some studies addressed both domains; therefore, the categories overlap and are not mutually exclusive.

Recurring Implementation Challenges

Beyond reported benefits, the review also identified recurring implementation barriers. These challenges were grouped thematically, as presented in Table 5.

Table 5. Thematic Categories of Implementation Challenges

Challenge Category	Description
Teacher Readiness	Limited experience in designing authentic problems and facilitating inquiry
Time Constraints	Pressure to complete curriculum targets within limited instructional time
Assessment Complexity	Difficulty evaluating inquiry processes and collaborative learning
Student Preparedness	Unequal participation and varying levels of autonomy
Resource and Technology Constraints	Limited access to digital tools and instructional materials

The recurrence of these themes across educational levels indicates that implementation challenges are not isolated to specific contexts. Instead, they reflect broader structural and pedagogical conditions that shape how PBL is enacted in science classrooms.

Discussion

The results of this review suggest that interest in Problem-Based Learning within science education has not diminished over time. Instead, the steady appearance of studies across recent years indicates that PBL continues to be viewed as a relevant instructional alternative. The noticeable increase in publications after 2020 may reflect broader educational shifts toward inquiry-driven and student-centered practices (Walker & Nouri, 2025). Rather than being treated as a temporary innovation, PBL appears embedded within ongoing conversations about improving the quality of science learning (Smith et al., 2022). This continuity strengthens the argument that examining its implementation and associated challenges remains necessary.

An important pattern emerging from the findings concerns methodological preference. The predominance of quantitative studies signals a strong emphasis on measuring outcomes in observable and statistically demonstrable ways. This orientation contributes valuable evidence regarding the effectiveness of PBL in enhancing learning performance. However, it also implies that fewer studies deeply explore classroom processes, contextual influences, or the lived experiences of teachers and students (Hagenah & Thompson, 2021). The limited representation of qualitative and design-based approaches suggests that implementation dynamics may not yet be fully understood. A broader methodological balance could therefore enrich future investigations (Jarodzka et al., 2021).

The diversity of implementation strategies highlights the flexible nature of PBL. While some studies follow conventional PBL stages closely, others adapt the model by incorporating digital platforms or combining it with complementary instructional approaches. Such variation illustrates that PBL functions more as a pedagogical framework than as a rigid procedure (Levin & Major, 2025). The integration of technology, in particular, indicates attempts to strengthen engagement and scaffold inquiry through contemporary tools (Carroll et al., 2021). At the same time, these modifications introduce new variables, such as technological accessibility and digital literacy, which may shape outcomes in significant ways.

With regard to learning outcomes, the dominance of cognitive indicators stands out clearly. Improvements in critical thinking, conceptual mastery, and problem-solving skills are consistently reported across studies. This pattern corresponds with the foundational principles of PBL, which emphasize analytical reasoning and structured inquiry (F. Chen & Chen, 2025). The strong representation of higher-order thinking measures demonstrates that researchers often evaluate PBL through its intellectual impact. While this focus is understandable, it also frames PBL primarily as a tool for academic performance enhancement (Smith et al., 2022).

Affective outcomes, though less frequently documented, reveal another important dimension of PBL implementation. Reports of increased motivation, strengthened scientific attitudes, and improved collaboration indicate that PBL may also influence learners' dispositions and engagement. These changes, although sometimes more difficult to quantify, are essential for sustaining interest in science over time (Constantino et al., 2022). The smaller number of studies examining affective domains may reflect challenges in measurement rather than limited impact (Cloos et al., 2023). Expanding assessment strategies could therefore provide a more balanced understanding of PBL's broader educational influence.

The persistence of implementation challenges across contexts underscores a critical tension between pedagogical ideals and classroom realities. Limited instructional time, pressure to meet curriculum standards, and difficulties in evaluating inquiry-based processes frequently constrain the depth of PBL activities. These recurring issues suggest that the effectiveness of PBL cannot be separated from institutional conditions (Wijnia et al., 2024). Even well-designed problem scenarios may not achieve their intended impact if structural constraints restrict meaningful exploration (Kaldaras et al., 2024).

Teacher and student readiness further shape implementation outcomes. Facilitating PBL requires instructional competencies that differ from traditional teaching practices, including guiding inquiry, managing collaborative interaction, and supporting independent reasoning (Anchunda & Kaewurai, 2025). At the same time, students must adapt to roles that demand greater responsibility and active participation. Variations in prior knowledge, autonomy, and communication skills can influence how effectively group-based learning unfolds (A. Li et al., 2023). Consequently, gradual scaffolding and sustained professional development appear central to strengthening implementation quality (Patfield et al., 2023).

Taken together, the findings indicate that PBL holds considerable promise for advancing science education, yet its success depends on contextual alignment. The consistent reporting of cognitive benefits confirms its capacity to foster higher-order thinking, while affective gains suggest broader developmental impact. However, recurring structural and pedagogical challenges demonstrate that adoption alone does not guarantee effectiveness (Radovan & Radovan, 2024). Sustainable implementation requires attention to curriculum design, teacher preparation, assessment practices, and resource availability (Weiss et al., 2021). By integrating patterns of implementation, outcomes, and barriers, this review offers a more comprehensive perspective on how PBL functions within science education and what conditions support its long-term viability.

Implications

The findings of this review carry several important implications for science education practice and research. First, the consistent reporting of cognitive gains suggests that Problem-Based Learning remains a strong pedagogical option for fostering higher-order thinking, particularly critical thinking and conceptual understanding. However, the recurring implementation challenges indicate that effectiveness depends heavily on contextual readiness, including teacher competence, curriculum flexibility, and resource availability. Therefore, professional development programs should move beyond introducing PBL procedures and instead focus on designing authentic problems, managing collaborative inquiry, and developing appropriate assessment strategies. At the institutional level, curriculum frameworks may need adjustment to provide sufficient time and structural support for inquiry-based learning. Moreover, the imbalance between cognitive and affective outcome reporting suggests that educators and researchers should adopt broader evaluation frameworks to capture both intellectual and dispositional dimensions of learning. In this way, implementation can be aligned more closely with the holistic goals of science education.

Limitations

Despite its comprehensive scope, this review has several limitations that should be acknowledged. The analysis was restricted to studies indexed in the Scopus database and published in English between 2017 and August 2025, which may have excluded relevant research from other databases or non-English contexts. Additionally, while the review synthesized implementation strategies and reported outcomes, it relied on the interpretations and reporting quality of the original studies. Variations in research design, measurement instruments, and contextual descriptions across studies may limit the comparability of findings. Furthermore, the categorization of outcomes into cognitive and affective domains does not fully capture the complexity of learning processes, as some studies addressed overlapping constructs. Finally, because this study employed descriptive and thematic synthesis rather than meta-analytic statistical aggregation, the conclusions emphasize patterns and tendencies rather than quantified effect sizes.

Suggestions

Future research should address several areas to deepen understanding of PBL implementation in science education. Greater attention should be given to qualitative and mixed-method approaches that explore classroom dynamics, teacher facilitation strategies, and student experiences in greater depth. Longitudinal studies may also provide insight into the sustained impact of PBL beyond short-term performance gains. Additionally, more balanced investigation of affective and metacognitive outcomes would help clarify how PBL influences learners' engagement and long-term interest in science. Research that examines contextual variables, such as school culture, resource distribution, and policy frameworks, could further illuminate the structural conditions that shape implementation success. Comparative studies across educational levels may also reveal developmental considerations that influence the effectiveness of inquiry-based learning. By expanding methodological diversity and contextual analysis, future investigations can contribute to a more nuanced and sustainable understanding of PBL in science education.

CONCLUSION

This review consolidates recent evidence on the implementation of Problem-Based Learning in science education and clarifies the challenges that repeatedly shape its classroom adoption. Based on 53 eligible studies, the literature shows that PBL is most often investigated through quantitative designs and is primarily linked to cognitive improvements, especially in critical thinking, conceptual understanding, and problem-solving performance. Affective outcomes, including stronger motivation, scientific attitudes, and collaborative dispositions, are also present in the evidence base, although they are reported less consistently and receive less emphasis than cognitive indicators. The synthesis further indicates that PBL is commonly enacted through varied formats, ranging from adherence to core PBL procedures to adaptations involving digital tools and combinations with other instructional models, demonstrating the approach's flexibility across science learning contexts. At the same time, persistent constraints, such as limited instructional time, curriculum coverage pressures, assessment demands, uneven teacher readiness, and differences in student preparedness, highlight that implementation quality is strongly dependent on contextual conditions. Overall, the findings confirm that PBL can meaningfully support science learning, yet its effectiveness and sustainability rely on thoughtful problem design, appropriate pedagogical support, and institutional arrangements that accommodate inquiry-oriented instruction. By integrating implementation patterns, reported outcomes, and recurring barriers, this review offers a clearer basis for strengthening PBL practice and guiding future research in science education.

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AUTHOR CONTRIBUTIONS STATEMENT

Faiz Mudofir contributed to conceptualization, data curation, formal analysis, methodology design, and drafting of the original manuscript. Edy Cahyono contributed to supervision, conceptual refinement, validation of methodology, and critical revision of the manuscript for important intellectual content. Sigit Saptono contributed to conceptual development, formal analysis, review and editing of the manuscript, and refinement of the discussion section. Sulhadi contributed to supervision, theoretical framing, interpretation of findings, and final manuscript validation. All authors reviewed, revised, and approved the final version of the manuscript prior to submission.

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