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Mapping STEM implementation in biology learning in Indonesia: Models, educational levels, outcomes, and challenges through a systematic literature review

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ABSTRACT

Although systematic reviews of STEM (Science, Technology, Engineering, and Mathematics) implementation in Indonesia have been widely conducted, previous studies have mainly focused on learning outcomes in specific educational contexts. Comprehensive mapping of STEM implementation in biology learning in Indonesia remains limited. This study aims to analyse the implementation of STEM-based biology learning in Indonesia. It employs the Systematic Literature Review (SLR) method following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. Data were sourced from publications indexed in Scopus and Google Scholar. The initial search identified 1,041 records covering biology, learning, and STEM. After applying the inclusion criteria, 77 articles on STEM-based biology learning published between 2015 and 2025 were selected as the final sample. The results indicate that Project-Based Learning (PjBL) (n=19) and Problem-Based Learning (PBL) (n=8) dominate the STEM models applied, while the STEM Engineering Design Process (STEM-EDP) (n=1) remains underrepresented. Implementation is concentrated in Java (n=40). Cognitive outcomes, such as critical thinking (n=19) and creative thinking (n=15), are more frequently reported than non-cognitive outcomes, such as motivation and scientific attitudes. The main challenges are teacher readiness (n=27), time constraints (n=8), and limited facilities (n=21), while student enthusiasm and the availability of learning materials serve as key supporting factors. The results have important implications for educational policymakers and biology educators, including promoting more equitable STEM integration, strengthening teacher professional development, and expanding the adoption of STEM-EDP approaches beyond Java. Future research should examine the effectiveness of underutilised STEM approaches, particularly STEM-EDP.

Keywords: Biology learning, STEM, systematic literature review

INTRODUCTION

As the world's largest archipelagic nation, comprising five major islands and thousands of smaller ones, Indonesia faces considerable challenges in providing equitable, high-quality biology education (Chang et al., 2014; Sukmayadi & Yahya, 2020). These challenges include limited laboratory infrastructure, disparities in access to educational technology across regions, varying levels of teacher preparedness, and the ongoing need to enhance students' scientific literacy. At the same time, biology learning is confronted with increasingly complex challenges arising from the rapid transformation of technology, which demands the integration of digital innovations, adaptive pedagogical approaches, and the development of students' 21st-century competencies to effectively navigate an evolving educational landscape (Hujjatusnaini et al., 2022; Kasap et al., 2024; Pamungkas et al., 2023).

In this context, an interdisciplinary approach that integrates biology with other disciplines has become increasingly important, particularly for addressing the gap between conceptual understanding and applied problem-solving skills that Indonesian students need to meet real-world challenges (Bai, 2025; Hiong & Osman, 2015; Vasquez et al., 2013). One approach that has attracted considerable global attention and is increasingly relevant to the Indonesian educational landscape is Science, Technology, Engineering, and Mathematics (STEM) education.

STEM education integrates four interrelated disciplines into a unified pedagogical framework designed to support contextual and real-world problem-solving (English, 2016; Kelley & Knowles, 2016). Unlike conventional teaching, which focuses on a single subject area, STEM integrates multiple disciplines to create learning experiences that foster students' scientific reasoning, technological application, engineering design processes, and mathematical analysis (Bybee, 2013; Holmlund et al., 2018). The interdisciplinary character of the STEM approach has made it a widely recognised educational framework and a strategy for equipping students with 21st-century skills (Breiner et al., 2012; Gonzalez & Kuenzi, 2012; Roehrig et al., 2021). Biology offers a natural fit for STEM integration because of the concrete, applied nature of its subject matter. Topics such as ecosystems and environmental problems can be explored through engineering design and technological tools for monitoring and problem-solving, while subjects such as biotechnology and organ systems lend themselves to mathematical modelling and scientific investigation that mirror real-world biological inquiry. This natural alignment positions biology as a strategic entry point for implementing STEM-based learning in schools.

STEM is key to building the capacity to adapt to the 4.0 industrial revolution and to contribute to enhanced societal well-being in the era of society 5.0 (Deguchi & Sameshima, 2020; Lase, 2019; Nusyirwan et al., 2020; Pereira et al., 2020). Consequently, many countries have moved towards incorporating STEM orientations into their education systems (Affandi et al., 2019; Laksmiwati et al., 2020). Indonesia has encouraged STEM-oriented learning practices within curriculum implementation, although STEM has not yet been formalised as a separate curricular framework. A STEM-based instructional approach using a contextual problem-based learning strategy nonetheless serves as a bridge between classroom theory and the demands of the real world (Kelley & Knowles, 2016; Nguyen et al., 2020).

Research findings indicate that implementing STEM in the classroom can enhance students' interest and motivation to learn, particularly in science and technology (Ribeirinha et al., 2025; Tsai et al., 2021). Several studies have reported positive effects of STEM-based learning on students' critical thinking, creativity, and problem-solving skills (Chen & Chen, 2021; Hebebci & Usta, 2022; Suherman et al., 2025).

Previous research on STEM-based biology learning in Indonesia has largely focused on assessing the effectiveness of specific learning models and on cognitive outcomes such as critical thinking and problem-solving skills (Cao et al., 2025; Hardiani, 2025; Irpan & Bhakti, 2022; Pohan & Fauzi, 2023; Rahman et al., 2023). Studies that comprehensively map broader dimensions, including the distribution of implementation across educational levels and regions, the range of learning outcomes beyond cognitive domains, and the challenges and enabling factors encountered in practice, remain scarce in the Indonesian context (Arlinwibowo & Kartowagiran, 2021; Farwati et al., 2021; Ilma et al., 2023).

To address this gap, the present study employs a Systematic Literature Review (SLR) approach, enabling a qualitative, descriptive synthesis of research trends, implementation patterns, and contextual dimensions that quantitative meta-analyses cannot fully capture (Bearman & Dawson, 2013; Marzi et al., 2025). Unlike previous SLR studies that focused on pure biology or general STEM trends (Chofifawati et al., 2022; Husamah et al., 2024), this study specifically examines how STEM is implemented in biology learning across educational levels and regions in Indonesia, including the disparity between Java and non-Java regions, and explores non-cognitive outcomes and structural challenges that have received limited attention in existing research. The novelty of this study therefore lies in its comprehensive synthesis of STEM implementation in biology learning in Indonesia across four dimensions: instructional models and biology topics, educational level and regional distribution, reported learning outcomes, and the challenges and supporting factors associated with implementation.

Specifically, this study aims to address four research questions (RQs). 1) What instructional models, approaches, and biology topics are used in implementing STEM-based biology learning in Indonesia? 2) At which educational levels and in which regions has STEM-based biology learning been implemented in Indonesia? 3) What learning outcomes are reported in studies of STEM-based biology learning in Indonesia? 4) What challenges and enabling factors are identified in the implementation of STEM-based biology learning in Indonesia?

METHOD

This study employs a Systematic Literature Review (SLR) to identify, evaluate, and synthesise empirical research on the implementation of STEM-based biology learning in Indonesia (Chigbu et al., 2023; Newman & Gough, 2020). The SLR approach was chosen for its ability to provide a comprehensive, systematic, and transparent overview of research trends, implementation characteristics, and reported learning outcomes (Ilma et al., 2023). The literature review followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses*)* guidelines, as illustrated in Figure 1, to ensure traceability and consistency throughout article selection (Megawati, 2024; Moher et al., 2009).

A systematic literature search was conducted across three electronic databases—Scopus, Google Scholar, and PubMed in January 2026. Google Scholar searches were conducted using Publish or Perish software (Harzing, 2007), with retrieval limited to the 1,000 most relevant records to ensure a manageable and systematic screening process. PubMed was included because, in addition to biomedical research, it indexes studies that integrate health-related topics with biology education, including vocational secondary education contexts.

Searching multiple databases was intended to maximise coverage and reduce the likelihood of missing relevant studies. After duplicate removal and eligibility screening, no studies retrieved from Scopus or PubMed met the inclusion criteria. Consequently, the final dataset comprised 77 studies, all of which were identified through Google Scholar.

Table 1. Inclusion and exclusion criteria

Criteria	Inclusion	Exclusion
Publication Years	2015-2025	Before 2015
Language	English and Indonesian	Languages other than English/Indonesian
Study Type	National or international peer-reviewed journals, conference proceedings	Literature review, conceptual paper, opinion article, book, editorials, newspapers, or blogs
Focus	The study investigates the implementation of STEM-based learning in biology learning contexts	The study does not involve biology learning, or STEM is implemented without integration of biology content
Education Level	elementary school (SD), junior high school (SMP), and senior or vocational high school (SMA/K)	Non-formal education
Geographical context	Implemented in Indonesia, or explicitly mention areas in Indonesia	The study is conducted outside Indonesia

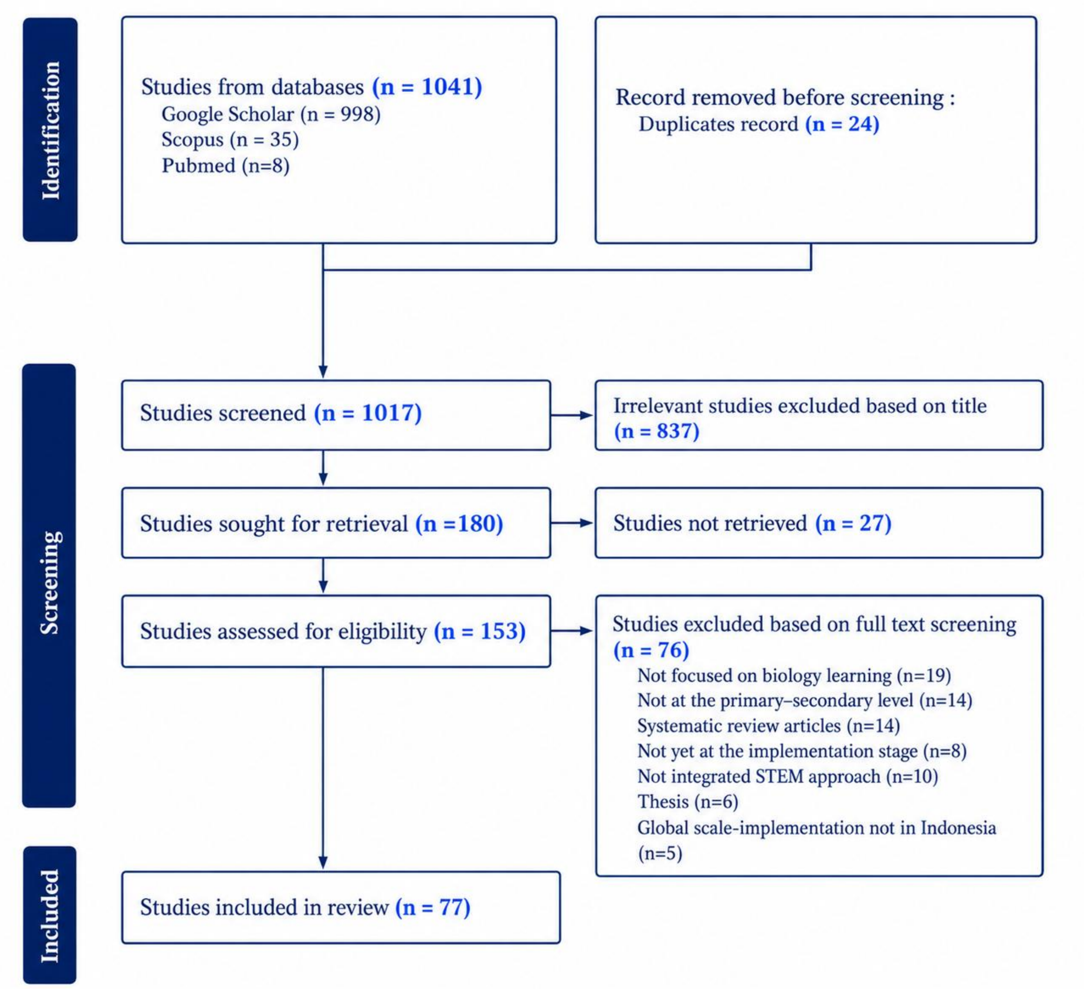

Figure 1. PRISMA flow diagram

The search strategy used a combination of keywords with Boolean operators (AND, OR) as follows:

- ("STEM learning" OR "STEM-based learning" OR "STEM education")
- AND ("biology learning" OR "biology education")
- AND ("Indonesia")
- AND ("elementary school" OR "junior high school" OR "senior high school" OR "secondary high school".

The articles included in this review were selected using systematically defined inclusion and exclusion criteria (Table 1).

Studies published between 2015 and 2025 were included because this period reflects the growing implementation and research interest in STEM education in Indonesia (Arifin et al., 2021). Studies published in 2026 were excluded because the literature search and screening were completed by the end of 2025, and 2026 publications had not yet been fully indexed in the selected databases. Articles written in English or Indonesian and published in reputable national or international journals, as well as conference proceedings, were considered, whereas literature reviews, conceptual papers, books, editorials, and blog posts were excluded. Studies included in this review were required to explicitly examine the implementation of STEM-based learning in a biological context; consequently, studies that did not involve biological content or meaningfully integrate STEM were excluded from the analysis. Furthermore, the review was restricted to formal education, with the geographical context of implementation limited to Indonesia or its regions. Only empirical studies reporting original data were eligible for inclusion. Research and development (R&D) studies were included provided they reported practicality and effectiveness outcomes derived from empirical testing with students, rather than validity assessment alone; eligible R&D studies were subsequently classified according to their instructional model and synthesised alongside the other empirical studies included in this review.

Article screening and selection were conducted by a single reviewer, which is acknowledged as a limitation of this study. However, a review protocol including inclusion/exclusion criteria was developed with the other authors prior to the screening process.

RESULTS AND DISCUSSION

An initial review of scientific publication data identified 1,041 articles addressing STEM within biology and learning contexts through 2025. This number indicates the high level of attention researchers have paid to integrating STEM into biology learning. Following the screening and eligibility process, a bibliometric analysis of the 77 included articles was conducted using VOSviewer software (Van Eck & Waltman, 2010), based on the co-occurrence of author keywords, with a minimum keyword occurrence threshold of 7. The bibliometric analysis of STEM research is presented in Figure 2. The figure reveals four colour-coded clusters indicating the following thematic groupings: (1) the red cluster represents the development of instructional materials, such as modules and learning media; (2) The green cluster represents the measurement of the effectiveness of STEM on student learning outcomes; (3) the blue cluster represents research methodologies, such as experimental and control class designs; and (4) the yellow cluster represents STEM integration. Keywords that have yet to appear in the bibliometric mapping include the implementation of STEM in the classroom and school infrastructure. Meanwhile, the educational level represented is limited exclusively to high school students, indicating that STEM research has remained predominantly concentrated at the secondary education level and has not yet substantially extended to the elementary education level. These bibliometric findings suggest that existing research has

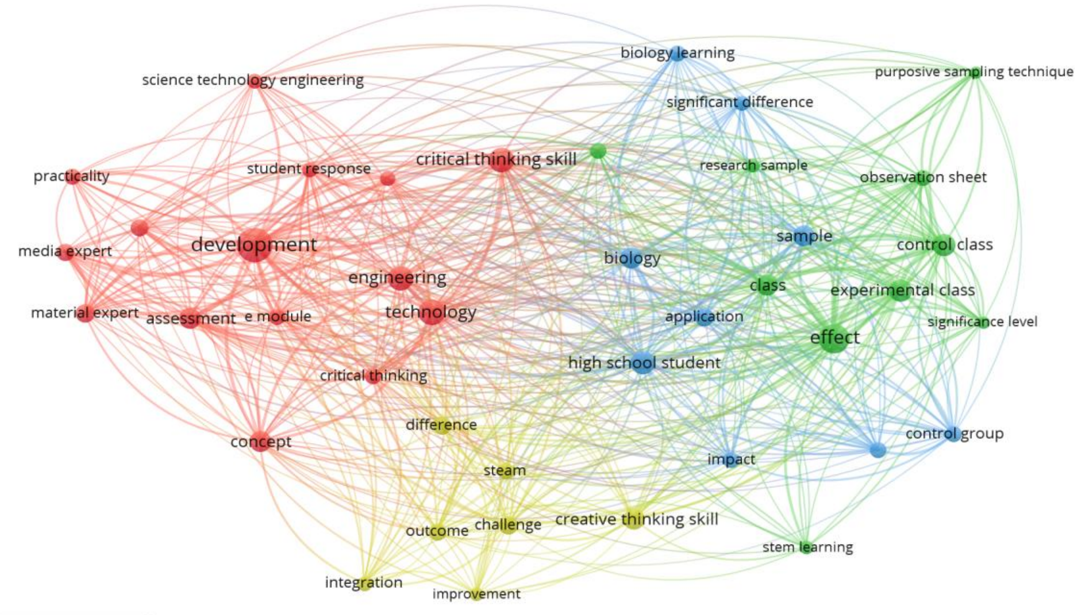

Figure 2. Network visualisation of each cluster

addressed the effectiveness of STEM. However, it has not yet sufficiently explored its implementation across the full spectrum of educational levels.

The findings from the selected articles (Figure 2) consistently demonstrate that STEM-based biology learning positively impact on students' higher-order thinking skill. This is consistent with the interdisciplinary nature of STEM, which encompasses problem-solving, critical thinking, and creative thinking, all of which directly enhance higher-order thinking skills (Baharin, et al. 2018).

Nevertheless, STEM has largely been framed as an instructional strategy to improve measurable learning outcomes, such as critical and creative thinking skills, rather than as a comprehensive approach that transforms teachers' instructional practices and the broader learning environment (Khotimah et al. 2021; Murnawianto et al. 2017).

Table 2 summarises the distribution of research topics across the 77 studies included in this review. Because several studies examine multiple learning outcomes, competencies, or instructional objectives, a single study may be classified into multiple topic categories if it addresses more than one learning outcome or research focus. Consequently, the cumulative frequency in Table 2 exceeds the total number of included studies (N = 77). The findings indicate that STEM implementation in Indonesian biology education has been examined predominantly in classroom-based learning contexts rather than within a formalised STEM curriculum framework (Agustina et al., 2020; Jayanto & Saputro, 2026). This observation aligns with previous studies suggesting that STEM in Indonesia is generally positioned as a pedagogical approach rather than fully integrated into a structured curricular framework (Nabila, 2025; Suwarma & Kumano, 2019).

In classroom-based learning, the implementation of STEM has been predominantly characterised by the adoption of Project-Based Learning (PjBL, n=19) and Problem-Based Learning (PBL, n=8). Both models are favoured for their ease of integration with biological content, their alignment with the assessment of higher-order thinking skills (HOTS) (Jayanto & Saputro, 2026; Safitri et al., 2025), and their structural compatibility with the foundational principles of STEM integration, namely the combination of multiple disciplines to address contextual problems through the design and production of real-world solutions (Capraro et al., 2013; Han et al., 2015; Krajcik & Blumenfeld, 2006). A content review found that biological content consistently served as the central focus of learning, while the other STEM components were integrated as supporting processes to facilitate students' understanding of biological concepts. Therefore, although the degree of integration varied across studies, the STEM components were not treated as separate learning objectives but rather as complementary processes that supported learning. This pattern is consistent with the nature of biology education, in which scientific concepts remain the primary learning objective, while technology, engineering, and mathematics provide the means for inquiry, design, analysis, and problem-solving.

The least frequently employed approach in biology learning is the integration of STEM with technology, specifically the STEM-Engineering Design Process (STEM-EDP) model (n=1), even though this approach is regarded as the most authentic, integrating all four STEM disciplines simultaneously (Κουμαρά et al., 2024; Tipmontiane & Williams, 2022). This limited adoption can be attributed to the more demanding prerequisites associated with STEM-EDP, including teachers’ competency in facilitating the design process and the availability of adequate school facilities (Abdurrahman et al., 2023; Sujarwanto et al., 2021).

The most frequently occurring biology topics in STEM research are Environmental (n=14), Ecosystem (n=12), Organ System (n=12), and Biotechnology (n=14). These topics are more

Table 2. Synthesis of findings across research questions (RQ1–RQ4)

Research Question (RQ)	Findings Category	Studies (n)
RQ1	Model/Approach of STEM Implementation:	
	a. PjBL-STEM	19
	b. PBL-STEM	8
	c. Discovery-STEM	2
	d. STEM e-module	11
	e. STEM–Learning Media	8
	f. STEM–Learning Strategy	5
	g. STEM–Digital Technology	6
	h. STEM–Contextual Integration	8
	Biology Topics Frequently Addressed :	
	a. Environmental Issues	14
	b. Ecosystem	12
	c. Organ System	12
	d. Biotechnology	14
	e. Biodiversity	5
	f. Genetics	1
	g. Virus, Monera, dan Protista	11
RQ2	Educational Level :	
	a. Secondary (SMA)	49
	b. Vocational (SMK)	2
	c. Junior (SMP)	22
	d. Elementary (SD)	2
	Regional Distribution :	
	a. Java Island	40
	b. Outside Java Island	33
RQ3	Cognitive Outcomes :	
	a. Critical Thinking	19
	b. Problem Solving	5
	c. Creative Thinking	15
	d. Scientific Literacy	10
	e. Concept Mastery	12
	f. HOTS	27
	Product Evaluation :	
	a. Validity and Feasibility	20
RQ4	Challenges Identified :	
	a. Limited Instructional Time	8
	b. Teacher Readiness	27
	c. Student Readiness	35
	d. Facilities and Resources / Infrastructure	21
	e. Curriculum Alignment and Other Challenges	6

commonly integrated into STEM because they are contextual, applicable, and linked to global issues such as pollution and sustainability, making it well-suited for solution-based projects (Alkair et al., 2023). Organ systems enable the development of models and simulations that connect science with health technology, while biotechnology is inherently interdisciplinary and product-oriented (Abdullah et al., 2025; Khairuna, 2023).

In contrast, genetics is relatively rarely integrated into STEM because of its higher level of conceptual abstraction and the complexity of the subject matter, which frequently lead to misconceptions and comprehension difficulties among students (Bowling et al., 2008; Machová & Ehler, 2023). This gap, however, can be viewed as an opportunity for future research, in which digital simulation, modelling, or engineering-design-based learning may help visualise abstract genetic concepts while reducing student misconceptions.

This study found that STEM-based biology learning is most frequently implemented at the senior high school level (SMA, n=49) and the junior high school level (SMP, n=22). Implementation remains relatively rare at the elementary school level (SD, n=2) and the vocational high school level (SMK, n=2). STEM integration is more successful at the senior high school level because the curriculum structure and depth of subject matter are better suited to project-based learning and interdisciplinary integration (Kemendikbud, 2016; Kemdikbudristek, 2022) . At the elementary school level, the instructional focus remains centred on foundational literacy, whereas at the vocational secondary level, STEM integration is often limited to specific vocational fields rather than to an integrated STEM framework (Nuragnia & Usman, 2021; Susanah, S. 2020).

Regarding regional distribution, STEM implementation is uneven and highly concentrated on Java Island (n=40). Other research findings also point to a similar trend: STEM is widely implemented, particularly in provinces such as DKI Jakarta, West Java, Central Java, and East Java (Kertati et al., 2024). The implementation of STEM remains concentrated on Java Island, due to better access to laboratories, technological equipment, and certified teachers (Azzizah, 2015; Çakır, 2025). STEM research is also quite extensive in Sumatra (n=20) but remains limited in Kalimantan (n=5). An interesting finding in this study is that STEM implementation is beginning to develop in Eastern Indonesia (n=8); this contrasts with previous researchers who reported that implementation in Eastern Indonesia was very limited (Farwati et al., 2021; Marthinu et al., 2026). The total regional distribution is less than the total number of articles (n=77) because several articles do not explicitly mention the geographic area of the research or the level of education where STEM implementation was carried out.

Based on the analysis, STEM-based biology learning is still dominated by cognitive outcomes, particularly critical thinking (n=19), creative thinking (n=15), problem-solving skills (n=5), and overall learning effectiveness (n=20). This dominance is likely due to the national education system, which still prioritises measurable academic achievement as the primary indicator of learning success (Hyytinen et al. 2025; Pahrudin et al. 2021). Critical and creative thinking represent the most frequently measured outcomes because both can be directly assessed through standardised test instruments, making them easier to measure and report (Puspita et al. 2025). Conversely, non-cognitive aspects such as motivation, scientific attitude, collaboration, and long-term impact are less frequently studied because they require more complex instruments (Mayes & Rittschof, 2021; Memari & Ruggles, 2025). This imbalance is noteworthy, as it points to one of the key gaps identified in this review; while cognitive outcomes have been extensively documented, non-cognitive dimensions remain markedly underexplored, despite their recognised role in sustaining long-term engagement with STEM. This is concerning, as non-cognitive outcomes strongly predict students' long-term interest in STEM careers yet remain largely overlooked in current research that focuses mainly on short-term academic gains.

The findings of this study also indicate that challenges such as time constraints (Yusriani et al., 2020), teacher readiness (Pandiangan et al., 2025; Susilo & Sudrajat, 2020), and a lack of facilities (Mabsutsah et al., 2023; Madani, 2020) frequently arise during the implementation of STEM-based biology instruction. This approach structurally requires interdisciplinary integration, complex planning, and project-based activities that take longer than conventional instruction (Chen & Wang, 2025; McLure et al., 2022; Wahid & Talib, 2017). Research indicates that STEM, particularly Project-Based Learning, requires time for problem exploration, design processes, revisions, and reflection, making it difficult to align with rigid school schedules (Hossain et al., 2024; Nugraha et al., 2023; Yustiningsih et al., 2024).

Additionally, many teacher-readiness issues emerged as recurring challenges across the reviewed studies, particularly in STEM integration and interdisciplinary instructional design. This finding suggests that many teachers continue to struggle to translate STEM principles into classroom practice (Sulaeman et al., 2022, 2024; Susilowati et al., 2025). The limitations of laboratory facilities, digital devices, and instructional materials further compound barriers to implementation, particularly in under-resourced schools, given STEM's heavy dependence on facility support for investigative and design-based activities (Ejiwale, 2013; Muzammal & Hashmi, 2022; Shernoff et al., 2017). Accordingly, the persistence of these challenges suggests that successful STEM implementation depends not only on instructional innovation but also on systemic support, including teacher preparation, adequate resources, and curriculum alignment (Agusnur, 2025). Enabling factors such as school support, curriculum flexibility, teacher collaboration, and professional development are often assumed rather than empirically verified in the reviewed studies (Ekawati et al., 2025; Glaze-Crampes, 2020; Hunaepi & Suharta, 2024). This obscures a critical possibility: that documented STEM success reflects the advantages of well-resourced schools rather than the pedagogical model itself, leaving implementation failures in under-resourced and 3T (frontier, outermost, disadvantaged) schools underrepresented. Without deliberate reporting of institutional context, claims of STEM effectiveness risk reflecting privilege rather than pedagogy.

The primary factor supporting the implementation of STEM-based biology instruction is the availability of instructional materials, such as modules, worksheets, and digital media, which help teachers implement it systematically (Mariati et al., 2025; Pitri et al., 2024; Radhifah & Lufri, 2024). Furthermore, student engagement and enthusiasm are significant strengths, as project-based approaches have been shown to enhance motivation and participation in learning (Firdausih & Aslan, 2024; Rochintaniawati et al., 2025).

Much of the existing STEM research on biology learning continues to focus on technical and instructional aspects within the classroom, and has not extensively addressed structural challenges, including teacher workload, curriculum mismatches, the lack of validated STEM-specific assessment instruments, and the need for sustained, systematic teacher professional development (Awang et al., 2025; Bull, 2025; Yang et al., 2025).

In practical terms, the limited presence of STEM-EDP in the literature, already noted, contrasts with the numerous STEM-PjBL and STEM-PBL studies, indicating a critical gap in both research and practice. These findings imply that LPTKs must reform their preservice biology teacher curricula by systematically integrating the Engineering Design Process into their courses, given that many science teachers feel unprepared to teach science courses integrated with engineering design due to a lack of engineering preparation in their prior education (Mumba et al., 2025; Ojeogwu & Mumba, 2026). Without restructuring biology teacher preparation programmes, this gap will persist, and pre-service biology teachers will continue to lack the competencies needed to implement STEM-EDP effectively.

The uneven distribution of STEM-biology research across school levels, with primary school largely underrepresented, constitutes a critical policy gap. International evidence shows that elementary school students are developmentally capable of engaging with STEM-based environmental biology topics such as climate change, water systems, ecosystems, and biodiversity, and that early exposure to STEM yields measurable gains in environmental literacy and creative problem-solving (Fernández-Huetos et al., 2026; Keum & Baek, 2025). Unlike junior high school and senior high school teachers, who have increasingly developed independent capacity for STEM implementation, elementary school teachers require deliberate policy support, including curriculum frameworks and contextualised environmental biology materials. As a result, elementary school is the most foundational yet most neglected level of STEM-biology implementation in Indonesia.

CONCLUSION

This systematic review highlights several implications for STEM-based biology learning in Indonesia. At the senior high school level, biology topics such as environmental biology, ecosystems, organ systems, and biotechnology are well-suited to STEM integration and have been widely implemented. Conversely, the junior high school level requires a clearer curriculum framework that links biology learning to authentic local problems, while the elementary school level remains underexplored and needs greater contextual focus on environmental biology. Although STEM-PjBL and STEM-PBL have demonstrated positive outcomes, STEM-EDP offers greater opportunities to develop systems thinking, creativity, and problem-solving through an iterative design process. To support its implementation, undergraduate biology education must rethink the teaching of ecology, biotechnology, and animal physiology, integrating these subjects with technology, engineering, and mathematics. Pre-service programmes should introduce STEM-EDP during pre-service training, while professional development for in-service teachers should prioritise ongoing collaboration through PPG (Pendidikan Profesi Guru).

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